PRELIMINARY DESIGN
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Faculty of Aerospace Engineering
Design Synthesis Exercise 2015

NORA

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Preface

"Human life is far more important than just getting to the top of a mountain."
- Edmund Hillary

This report presents the time and effort invested into the design of an aerial system that is to assist mountain rescue teams in their harsh operations. It was a true honour to be able to contribute to the men and women that risk their lives to save those of others. We are pleased to clarify our journey by means of this document and are looking forward to facing new challenges for Project Nora

For the progress and results, the team is grateful to all, both individuals as well as teams and organisations, who helped to realise the concept of the aerial search and rescue assistance UAV. First of all, we would like to thank Santiago Garcia, Bruno Santos and David Blom for their supervision and invaluable advice. Additionally, we would like to express our gratitude towards search and rescue operators around the globe who informed us of their hands-on experience on their daily work. Their contribution has led to this piece of work, supported with information by the parties targeted for the design of Nora.

Delft, 30 June 2015

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Roman Symbols

Symbol	Description	Unit
E	Young's Modulus	$[Pa]$
I	Moment of Inertia	$[m^4]$
$\dot{P}$	Roll Rate	$[rad\, s^{-1}]$
A	Aspect Ratio	[-]
A	Availability	[%]
$a.c.$	Aerodynamic Centre	$[-]$
Ah	Capacity	$[A\, h]$
b	Wing Span	$[m]$
C	Maximum Discharge	$[h^{-1}]$
c	Chord Length	$[m]$
$c.g.$	Center of Gravity	$[-]$
C_X	Nondimensional coefficient of parameter X	$[-]$
D	Diameter	$[m]$
D	Drag	$[N]$
D	Fatigue Factor	$[-]$
dh	Vertical Gap	$[m]$
dx	Horizontal Gap	$[m]$
e	Oswald Efficiency Factor	$[-]$
F	Force	$[N]$
g	Gravitational Constant	$[m\, s^{-2}]$
h	Heat Transfer Coefficient	$[-]$
h	Transfer Coefficient	$[-]$
i	Index	$[-]$
K	Gain	$[-]$
k	Empirical Factor	$[-]$
L	Lift	$[N]$
l	Discretised Section Length	$[m]$
l	Length	$[m]$
L/D	Lift over Drag Ratio	$[-]$
M	Mach	$[-]$
M	Moment	$[N\, m]$
m	Mass	$[kg]$
N	Number of Flights	$[-]$
P	Power	$[J]$
p	Signal Received	$[dB\, m]$
Q	Pitch Rate	$[rad\, s^{-1}]$
q	Shear Flow	$[N\, m^{-1}]$
R	Cross-correlation	$[-]$
R	Radius of Gyration	$[m]$
R	Radius	$[m]$

R	Reliability	$[\%]$
R	Yaw Rate	$[rad\, s^{-1}]$
r	Distance Between a.c. and 3/4 Point	$[m]$
rc	Rate of Climb	$[m\, s^{-1}]$
S	Surface Area	$[m^2]$
T	Temperature	$[K]$
T	Thrust	$[N]$
t	Duration of Operational Cycle	$[h]$
t	Thickness	$[m]$
t	Time	$[s]$
t_{roll}	Roll Time to Achieve Φ_{des}	$[s]$
V	Speed	$[m\, s^{-1}]$
W	Required Cooling Power	$[W]$
W	Weight	$[N]$
x_z	Distance Between the c.g. and the a.c. of Surface z	$[m]$
y	Distance from Fuselage Centerline	$[m]$

Greek Symbols

Symbol	**Description**	**Unit**
λ	Sweep Angle	$[deg]$
α	Angle of Attack	$[deg, rad]$
β	Angle of Side Slip	$[deg, rad]$
$\ddot{\theta}$	Pitch Angular Acceleration	$[rad\, s^{-2}]$
δ	Angle of Deflection	$[deg, rad]$
Γ	Irrotational Vortex	$[m\, s^{-1}]$
γ	Flight Path Angle	$[deg, rad]$
λ	Failure Rate	$[h^{-1}]$
$\Lambda_{\frac{1}{2}}$	Half Chord Sweep Angle	$[deg]$
ω	Natural Frequency	$[s^{-1}]$
Φ	Bank Angle	$[deg, rad]$
ρ	Air Density	$[kg\, m^{-3}]$
τ	Control Surface Effectiveness	$[-]$
τ	Shear Stress	$[Pa]$
θ	Angle of r and Airfoil	$[rad]$

Subscripts

Symbol	**Description**	**Unit**
0	At Zero Lift	[-]
α	Derivative to α	[-]
β	Derivative to β	[-]
A	Aileron	[-]
ac	Aerodynamic Centre	[-]
b	Basic	[-]
c	Canard	[-]
cr	Critical	[-]

D	Differential	[-]
D	Three Dimensional Drag	[-]
e	Elevator	[-]
e	Engine	[-]
eff	Effective	[-]
f	Fuselage	[-]
$fail$	Until failure	[-]
fs	Fuselage Side	[-]
h	Horizontal Tail	[-]
I	Integral	[-]
i	Inboard	[-]
i	Induced	[-]
L	Three Dimensional Lift	[-]
m	Moment	[-]
n	Directional Stability	[-]
o	Outboard	[-]
P	Proportional	[-]
R	Rudder	[-]
r	Root	[-]
ss	Steady-state	[-]
T	Torque	[-]
t	Tip	[-]
v	Vertical Tail	[-]
w	Wing	[-]
xx	Around X-axis	[-]
yy	Around Y-axis	[-]
zz	Around Z-axis	[-]

List of Abbreviations

3GPP $3^{rd} Generation Partnership Project$
ABS Acrylonitrile Butadiene Styrene
AERO Aerodynamics
BEP Break-Even Point
CFD Computational Fluid Dynamics
CFRP Carbon Fibre Reinforced Polymer
CG Center of Gravity
CTRL Stability & Control
DC Direct Current
DET Detection
DRI Detection, recognition and Identification
DRV Driving Requirement
DSE Design Synthesis Exercise
EASA European Aviation Safety Agency
ELE Electronics
EPM Electro Permanent Magnet
EPS Expanded Polystyrene
FAA Federal Aviation Administration
FBD Free Body Diagram
FBS Functional Breakdown Structure
FFD Functional Flow Diagram
FOV Field of View
FPGA Field-Programmable Gate Array
FWE Food, Water & Equipment
Gen Generator
GPIO General Purpose Input/Output
GPRS General Packet Radio Service
GPS Global Positioning System
HDMI High-Definition Multimedia Interface
IC Combustion Engine
IMU Inertial Measurement Unit
IP Internet Protocol
IR Infrared
ISM Industrial, Scientific and Medical
KEY Key Requirement
KIL Killer Requirement
LKP Last Known Position
LOS Line of Sight
LS Live Stream
MAT Materials
MCMT Mean Corrective Maintenance Time
MNF Manufacturing
MTBF Mean Time between Failures
MTTF Mean Time to Failure
MTTR Mean Time to Repair
NAV Navigation
NFOV Narrow Field of View
Nora Novel Rescue Assistance
PCB Printed Circuit Board
PE Processing Element
PID Proportional Integral Derivative
PLS Point Last Seen
POA Probability of Area
PROP Propulsion
PWR Power
RAMS Reliability, Availability, Maintainability & Safety
RPM Rounds per Minute
RTM Resin Transfer Moulding
SAR Search & Rescue
SATA Serial Advanced Technology Attachment
SH Stakeholder
SSD Solid State Drive
STOL Short Takeoff & Landing
STR Structures
TBD To Be Determined
TDOA Time Difference of Arrival
TELE Telecommunication
TU Delft Delft University of Technology
UAS Unmanned Aircraft System
UAV Unmanned Aerial Vehicle
ULF Ultimate Loading Factor
USB Universal Serial Bus
V&V Verification & Validation
VHF Very High Frequency
VTOL Vertical Takeoff and Landing
WFOV Wide Field of View

Executive Summary

Mountain ranges all over Earth have long been tourist attractions for their monumental size, beautiful nature, clean air and possible leisure activities. Though attractive, mountain activities may form a threat to human safety. Search and rescue (SAR) teams are constantly stand-by and often have multiple rescue sorties per day. These missions are slow and dangerous for the involved personnel. In extremely rare cases rescue missions use helicopters for search by pilot eyesight. These mission types on average cost €3,300 per hour, are dangerous for personnel, have a small endurance and have a large downtime. There is a clear need to improve effectiveness and safety of these rescue missions. To achieve this improvement, ten students at Delft University of Technology have designed an unmanned aircraft system (UAS), called *Nora*, as part of the Design Synthesis Exercise (DSE) concluding the Aerospace Engineering Bachelor degree. This Final Report describes the Final Design Phase of the DSE and succeeds the *Project Plan*, the *Baseline Report* and the *Midterm Report*.

Market Analysis: In order to come up with a feasible design, the problem at hand was analysed by means of identifying relevant stakeholders and performing a market analysis. This analysis described how mountain rescue operations are currently performed and how helicopters may assist during such missions. Specialists in the field of mountain rescue were contacted, through which was disclosed that in some countries, governmental authorities with nationwide departments are responsible for the rescue of missing individuals, whereas in others private organisations working mainly with volunteers are responsible. Furthermore, it could be concluded that each missing person is usually found within a radius of $25km$ of their last known position. The way the missing person behaves can greatly vary. A tailor-made plan is therefore set up for each individual mission, although grosso modo rescue missions start at the last know position of the missing person. Rescue workers on foot search the area systematically and thoroughly.

Based on the market analysis, a set of requirements was established. Most important were the requirements stating that the system shall be carryable by a group of three people on foot, shall have a maximum wingspan of $1.5m$, should have an endurance of at least two hours and should be able to autonomously detect a human in mountainous terrain of up to $5000m$ with extreme weather conditions of temperatures ranging from $-40°C$ to $60°C$ and gusts up to $100kmh^{-1}$.

Concept Design: From the *Baseline Report* and the *Midterm Report* it was found that a hybrid configuration was the best solution. Further analysis based on conversations with experts in the *drone industry*, as well as aerodynamics specialists focused the hybrid design on a conventional winged canard configuration with a push propeller, boasting quadcopter-like performance through its four vertical propellers.

This hybrid configuration was worked out in more detail in the Final Phase. For this, first the usual search and rescue mission was analysed. This process included estimating a mass budget ($11kg$ for *Nora*) and establishing different search techniques. With *Nora*, the SAR personnel can decide to search along a path, using a spiral motion or using mountain altitude lines to save energy, using a tablet interface. All search options are able to determine the ground elevation at all locations with a ground resolution of $30m$ by $30m$. This information is used as a first approach to avoid mountain collision.

Aerodynamic Design: In an iterative manner, the Final Design phase centred around the aerodynamics, power & propulsion, structures & materials and control & stability subsystem designs. The aerodynamics design primarily focused on optimising the relative size and placement of the two wings for lift over drag performance. Secondary considerations included stability and controllability. The canard-wing interaction was first quantified using rectangular wings as a simple, first order model. On this tandem system, Weissinger's approximation was applied. Several design iterations converged to a main wing roughly double the size of the canard with the NACA2415 airfoil as optimal for both wings. Due to several constraining conditions, such as the maximum span requirement and the accommodation of the rotors, the planform has an optimised, unconventional shape. The installed angle of attack, or incidence angle, should be $-0.75°$ for the main wing and $4.5°$ for the canard. A tail was sized to provide lateral stability and the body was shaped to incorporate all payload items. Furthermore the ailerons, elevators and rudder have been designed to control *Nora* during all flight phases under all conditions. Finally, an

estimate of the additional parasitic drag of the rotors and landing gear was found. The zero-lift drag coefficient was found to increase by 91% (meaning a cruise drag increase of 35%).

Powertrain Design: The powertrain consists of a combustion engine that runs on gasoline combined with five electrical motors that drive the propellers. Four of the electric engines are used for hovering while one electric engine is used for cruise flight. The power provided by the combustion engine is transformed into electrical energy using a small-scale generator. Excess energy that the combustion engine provides is stored in an accumulator. The combustion engine can provide a continuous power of $2200W$ and the accumulator has a voltage of $22.2V$. Within the total mass budget of the final design, *Nora* will have an endurance of two hours. Using the full capacity of the fuel tank, an endurance up to six hours can be achieved. Thereby increasing the characteristic coverage area per mission. The fuel tank was sized for additional volume in earlier iterations to account for this.

Structural Design: The structure had to be designed for very high loading factors of up to $12g$ due to the weather conditions it has to overcome. Preliminary estimates confirmed this notion and showed the structures and materials subsystem to have the largest impact on *Nora*'s overall mass. This backdrop formed the basis for the structural design methodology, and meant the design rationale was focused on weight reduction through structural optimisation and effective material choice. For this purpose, an optimised foam-carbon fibre structure has been used throughout the design to yield at ultimate Von Mises with solely differing titanium wing-fuselage connectors as well as the plastic landing gears. Furthermore, for maintainability and ease of use purposes, the fuselage has been designed with multiple cutouts located strategically on the top and bottom halves to cover 80% of the entire length of *Nora*. The other 20% can also be reached through these cutouts. The designed wings have lightweight click-and-go titanium connectors making the structure easily separable in an estimated time lower than $15min$ from backpack to air. The overall structural design cost, including manufacturing, has been estimated and validated through experts in the field at €3,900 with a total mass, including all internal and external appendages, of $4.5kg$.

Controller Design: *Nora* will use a PID controller to provide the required autonomous flight capabilities and provided artificial stability where needed. The PID controller is able to control *Nora* during nominal conditions and will be updated in a further design stage.

Search: A critical part of the operation is finding the missing person. Optical and thermal imaging are the primary form of detection. The thermal imaging module, made up of a *BAE Systems* thermal sensor and *Fujifilm* motorised zoom lens, is designed to fly at a constant $240m$ altitude. The latter may be used in conjunction with Johnson's Criteria, which implementation led to a ground coverage of $21km^2$ per hour based on a velocity of $30ms^{-1}$. Equating *Nora*'s probability of detection to those of human SAR teams, *Nora* was found to have a comparable search capability of 30 SAR members per hour. Johnson's Criteria on target identification will be achieved with predefined zoom lens, supplemented with a custom *DS8231 Ultra Precision Servo* driven image pointing system. The detection subsystem additionally contains a radio frequency sensor that can detect radio signals such as those from mobile phones. Finally, multiple sound sensors can be implemented in the system to increase the probability of detection.

Rescue: After finding the missing person, the first aid package must be delivered. When the vehicle is not able to land, it will drop a first aid package nearby whilst making sure that the person is not injured in the process. The content of the package includes a telephone which allows communication with *Nora* and the SAR team, food and water supplies, heat provisions and regular first aid supplies such as bandages. The package consists of a shell and an impact attenuator that is capable of dissipating 480J. This is equivalent to a 50% energy reduction for a drop from about $50m$. If the package is dropped from this altitude, the maximal g-loading the package experiences is $800g$ for a time of $2ms$. An additional impact foam can be found between the attenuator and the shell that further reduces this load by 80%, leaving a net impact loading of $160g$. All the content in the package has been verified to withstand this load for this amount of time.

Communication Design: When all system characteristics were determined, the internal and external communication were worked out in detail and visualised using hardware, software and communication flow diagrams. The external communication is a necessity, as the search and rescue personnel have to be able to follow the steps taken by *Nora*. For external communication, *Nora* is able to establish a direct Line-of-Sight (LOS) data link with the ground unit when operating within $10km$ range, as well as a satellite communication data link for out-of-sight or long range communication. To establish these connections, *Nora* is equipped with one $1.6GHz$ transceiver with corresponding antenna, integrated in the tail, for satellite communication at a data rate of $20kbit/s$ using the *Inmarsat Network*. For the LOS-connection, *Nora* is equipped with a $915MHz$ transceiver (or $433MHz$ depending on the region) with corresponding antenna for a two-way data link at $100kbit/s$ up to a range of $10km$ used for control and navigation of the UAV. *Nora* also possesses two transmitters (one at $2.4GHz$ and one at $5.8GHz$) with corresponding antennas for image transferring from UAV to ground unit, up to a distance of $3.0km$ from ground unit. The LOS communication is favoured over the satellite communication due to higher possible data rates and lower costs for data transmission and *Nora* will therefore always try to switch to LOS communication when possible.

Cost Analysis: Table 1 shows the cost and mass budget of all the subsystems of *Nora*. As can be seen, the estimated mass of $11kg$ was precisely achieved. This is because the fuel tank can be filled up as much as is possible within the requirements, to increase the endurance. The cost for one *Nora* turned out to be €13,700. With an estimated operational cost of €52.50 per hour including maintenance.

Table 1: Component Budget Breakdown

Subsystem	**Price [€]**	**Mass [kg]**
Propulsion	470	2.1
Structures	3900	4.5
Detection	7400	0.61
Control	320	0.031
Collision Avoidance	119	0.13
Data Handling	310	0.14
Communications	1100	0.14
Package	-	2.6
Fuel	-	0.57
Total	**13700**	**11**

Return on Investment: A return on investment analysis showed a break-even point would be reached at a minimum cost price of €25,000 for an optimal debt-equity ratio of 15% assuming 123 *Nora*'s would be sold according to the conducted market analysis. This would entail a compounding yearly net cash profit of 5.2% or 42% for a seven year period.

Separability: Since *Nora* had to be carried by men on foot, she was specially designed to be separable. It was found from the market analysis that the first responders that go out on mission are with a group of three persons all capable of carrying $8kg$ at maximum. This results in $24kg$ for the total system. In the table above it can be seen that the vehicle weighs $11kg$ in total. Next to this a $1kg$ tablet is needed for the control of the vehicle. Furthermore $6kg$ must be taken along with food, water and equipment for the responders. To carry everything, three backpacks must be designed, together weighing no more $3kg$. All this together with a $3kg$ contingency sums up to $24kg$. The backpacks must still be designed and should focus on being light weight and to allow for the special part forms of *Nora*. In conclusion *Nora*'s system will weigh $15kg$ in total.

1 | Introduction

Every year more and more people are visiting the mountains, often heading out unprepared that may lead to those people getting lost or injured. It can take a very long time for rescue workers to find someone, if they are found at all. The increasing amount of casualties puts the rescue workers under a high work pressure while workers are often volunteers and have regular jobs next to their rescue activities. Therefore there is a need to reduce the search time, to relieve the rescue workers and provide better aid to missing persons in the mountains.[1]

This report discusses the preliminary design of a hybrid UAV called *Nora* which will provide search and rescue assistance to the teams operating in mountainous areas around the world. This will be done by first summarising and extending the most important results from the *Midterm Phase*, followed by the performance of the iterative preliminary design process between the different disciplines. These are aerodynamics, structures, power and propulsion, detection, communication and electronics, resulting in a final coherent design. Afterwards several design characteristics are assessed and the future processes and planning are discussed.

The first five chapters mainly summarise the work done in the Baseline and Midterm Phases. Chapters 2-4 are an summarized and updated version of their equivalent chapters in the *Midterm Report*. Subsequently, in Chapter 5, the killer, driving and key requirements of *Nora*'s system, are listed. Chapter 6 provides a brief summary of the conceptual design process, determined in the *Midterm Report* resulting in the conceptual hybrid configuration, is given.

In Chapter 7, the operational mission is described. In this chapter, firstly, the mass budget estimation was performed, followed by the description of the search modes, based on market analysis. Subsequently the *Nora* user procedures were described and finally an overview of the mission interface is given.

In Chapters 8-9, the preliminary operational and vehicle design is outlined. In the former, the communication and detection subsystem are described first, followed by an elaboration on internal data handling and needed software for these subsystems. Subsequently the collision avoidance system is explained. Finally a backpack to carry *Nora* is designed, due to a lack of suitable backpacks available on the market. In Chapter 9, the simulator, essential to test the interaction of the subsystems, and the design of the subsystems itself are elaborated. These subsystem sections were divided into aerodynamics, power and propulsion, stability and control, and structures and materials of *Nora*. This chapter is closed with a description of the first-aid kit, extended with the design of the package shell and impact attenuator for package delivery and the dropping mechanism inside the fuselage.

Chapter 10 commences with an explanation and overview of the final configuration and layout. This is followed by a description of the different predefined system characteristics. Subsequently, examples of mission profiles are described . Furthermore, an analysis on the performance of *Nora* is executed and the sensitivity of different parameters on the subsystems are tested. Moreover, requirement compliance is given. Additionally, the breakdown of cost, mass and power is presented, followed by the performed risk management. Finally, the RAMS characteristics are analysed and an elaboration on the made sustainability choices is shown.

In the final chapter, firstly the future project steps are discussed. Subsequently the production plan is given, followed by the verification and validation procedures.

[1]URL `http://www.ukclimbing.com/articles/page.php?id=1575`, [cited 23 June 2015]

2 | Project Setup

The purpose of this chapter is to give a description of the project setup. First the project objective is given in Section 2.1. This includes the design exercise as presented at the beginning of the project. This is followed by the project logic in Section 2.2, in which the different phases within the design are characterised. Finally, the project organisation is presented in Section 2.3.

2.1 Objective

The *Design Synthesis Exercise* (DSE) is the final project done within the Bachelor of Aerospace Engineering at Delft University of Technology. Within this DSE, ten students are required to make a design in the field of aviation, space, earth observation, wind energy or a field closely related. In the design project the student is provided with an opportunity to obtain "design experience". This means the students go through the complete design process. This process starts with setting up requirements for the defined problem. Subsequently, concept analysis and design is performed, followed by a trade-off to select a concept. One of these concepts will be worked out in detail and presented in the Final Report. All of this is done in a structured and iterative manner.

Mountain High is the project in which ten students were given the opportunity to, in a period of ten weeks, design an unmanned aerial vehicle able to assist current search and rescue operations. The goal of the project is to design aerial support for mountain search and rescue teams for localising and provision of first-aid to missing people.

2.2 Logic

In this section, a broad overview of the *Mountain High* project will be given. Figure 2.1 shows the project logic diagram. In this diagram, a clear distinction is made between the activities that have to be performed on the vertical axis and the phases of the projects on the horizontal axis.

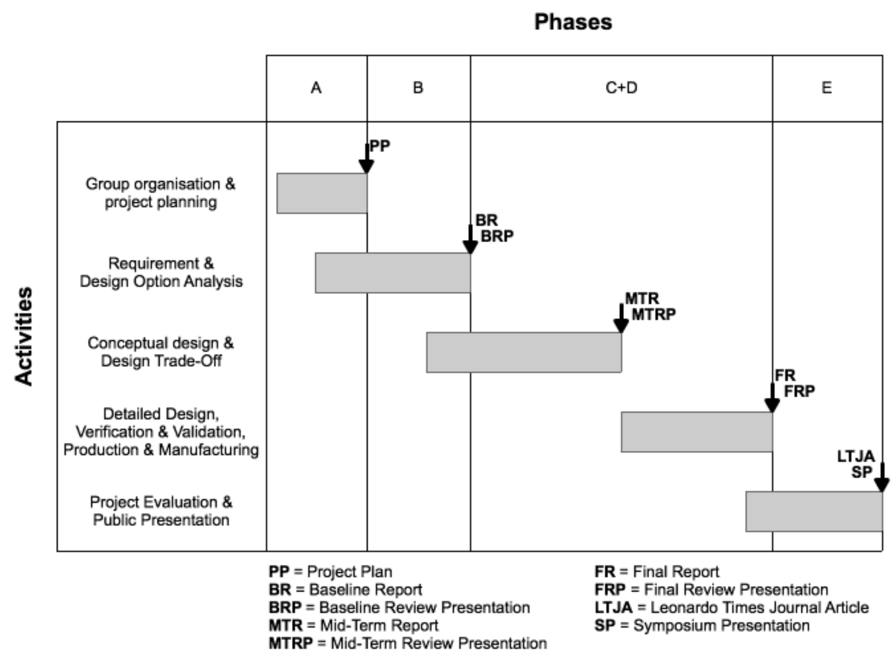


Figure 2.1: Project Logic Diagram

Phase A: Organisational Phase

The first phase is the Organisational Phase. In this phase it is made sure that the project will proceed efficiently. To accomplish that, the group members are assigned functions with respective tasks and the project work is structured. The decisions made during this phase are documented in the *Project Plan.* [1]

Phase B: Baseline Phase
In the Baseline Phase, the total set of requirements is conceived and structured. By using these requirements, a complete Design Option Tree is set up. After thinking of all the options, the designs that cannot comply with the established requirements are eliminated. The Baseline Phase is concluded by a *Baseline Report* as well as a *Baseline Review Presentation* to the principal tutor and coaches. [2]

Phase C+D: Design Phase
After making a very rough selection of design concepts, the Design Phase starts. This phase is immediately split up in the Conceptual Design Phase and the Preliminary Design Phase. The former focuses on working out the remaining design concepts and performing a trade-off. The results of the Conceptual Design activities are stated in the Mid Term Report and summarised in the Mid Term Review Presentation. The latter phase starts after the design trade-off has resulted in the most suitable design. This design will then be worked out in detail in this report. [3]

Phase E: Project Wrap-Up
In the last phase of the project, several activities will be performed to finalise the project. The final design and the entire process will be evaluated. Moreover, the design will be publicly presented with an article, a poster and a presentation in the DSE symposium design competition.

2.3 Organisation

In the *Mountain High* project each group member was given a non-technical function. In Table 2.1, an overview of these functions is given, together with the technical function of each group member during the Final Design Phase.

Table 2.1: Task Division for the Mountain High Project

Group Member	Student Number	Non-technical function	Technical function
M.M.A. Baert	4226542	Chief Software Engineer	Power & Propulsion Simulator
E.S. Bakker	4233816	Time Manager	Detection
M.H.H. Kemna	4217209	Chairman	Detection
H.M.J. Klijn	4230108	Secretary	Control Simulator
R.P.F. Koster	4147847	Chief Documentation	Communication
Y. Toledano	4118634	Project Manager	Structures
C.J.W. van Verseveld	4172256	Chief Presentations	Aerodynamics
C. Vertregt	4201159	Chief Editor	Aerodynamics
B. Vonk	4233077	Lead Engineer	Structures Computer-Aided Design
D. Willaert	4234820	Risk Manager	Power & Propulsion Communication

3 | Problem Analysis

The following chapter contains the Problem Analysis, performed during the Baseline and Midterm Phase of the DSE. First the mission tasks and goals are listed in Section 3.1. From these tasks, the functional breakdown structure (FBS) and functional flow diagram (FFD) are set up in Section 3.2. Furthermore, the project statements are defined in Section 3.3, followed by an elaboration on the stakeholders in Section 3.4.

3.1 Mission Goals

At the beginning of DSE, information was provided on the problems that currently exist in search and rescue operations. Land means are slow and can endanger the rescue workers searching for a missing individual. Therefore an unmanned aerial vehicle, *Nora* is needed to assist the existing search operations. *Nora* was designed in a period of ten weeks during the *Mountain High* DSE project. The goal of the project is to design a UAV that will assist current search and rescue teams. The defined tasks for *Nora* are listed below.

- *Nora* has to make current rescue operations more efficient.
- *Nora* has to be carried into the mountain by search and rescue teams.
- *Nora* has to be able to locate missing persons.
- *Nora* has to drop a first aid package to assist the potentially injured person.
- *Nora* has to be capable of working around in mountainous terrain around the entire world.

3.2 Functional Project Diagrams

The FFD and the FBS are essential elements in the design process. In Subsection 3.2.1, the breakdown structure for *Nora*'s Search and Rescue (SAR) mission is given. Finally, the *Functional Flow Diagram* including the logical ordering of functions of both the UAV and the Ground Unit are presented in Subsection 3.2.2.

3.2.1 Functional Breakdown Structure

The FBS of the unmanned aerial SAR assistance mission is shown in Figure 3.1. This diagram lists the top level functions that the mission has to fulfill in order to be successful. A distinction has been made between the UAV, the Mobile Ground Unit and the Incident Control. The Mobile Ground Unit consists of the rescue workers operating the UAV and the equipment they carry to do so. The Incident Control has responsibility of the operations as a whole, allocating teams over the search area.

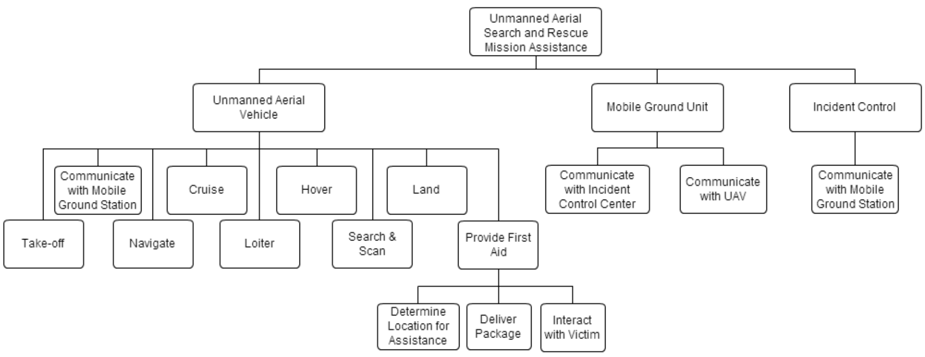


Figure 3.1: Functional Breakdown Structure

3.2.2 Functional Flow Diagram

The FFD of *Nora* can be found in Figure 3.2 and the FFD of the Ground Unit can be seen in Figure 3.3. A brief explanation of the AND and OR trees will be given. These trees either indicate all parallel activities to be completed in the order provided or a choice between the required options. As such, the OR-trees indicate the different design paths that can be taken, whilst the AND-trees indicate the fixed steps. A succinct explanation of ordering of functions follows below.

Nora

- *First OR-Tree (7.0):* The first OR-tree indicates the possibility of misdetection. When the ground rescue workers identify the missing person, *Nora* will move on to the first aid delivery stage. However, when the UAV misdetected another individual or object, it will continue to search.
- *Second OR-Tree (8.0):* The second OR-stage deals with the method of providing the first aid package. The supplies can either be dropped from above with high precision or the system can land near the victim and proceed from there. The used method is decided by the ground rescue team.
- *Third OR-Tree (10.0):* Assuming *Nora* has landed near the victim to provide the first aid package as well as the required interactions, it can then either depart again in order to search for other missing individuals or stay near the missing person till help has arrived.
- *Final OR-Tree (13.0):* Once the package has been dropped, *Nora* can opt for three possibilities. It can loiter over the victim, it can continue its search if more victims are missing or it can find an appropriate spot to land nearby the victim, since landing at the exact victim location was deemed to be impossible.

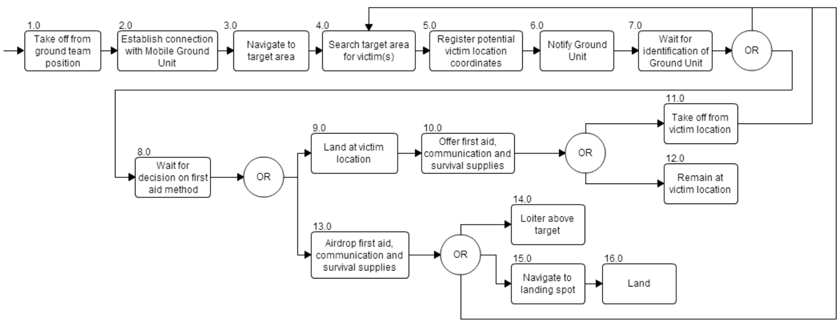


Figure 3.2: Functional Flow Diagram of *Nora*

Ground Unit

- *First AND-Tree (2.0):* This tree ensures that a connection with both the aerial vehicle and the Incident Control is established.
- *First OR-Tree (6.0):* This tree depicts three different options. The ground personnel could decide to leave the mission as it is, change the area in which *Nora* is searching, or (if the systems detected something) go on to the identification phase.
- *Second OR-Tree (11.0):* This tree shows the decision to either go to the victim location as fast as possible, or to use a helicopter for picking up the victim. The last option would be useful when the victim is injured or if the location is impossible to reach.

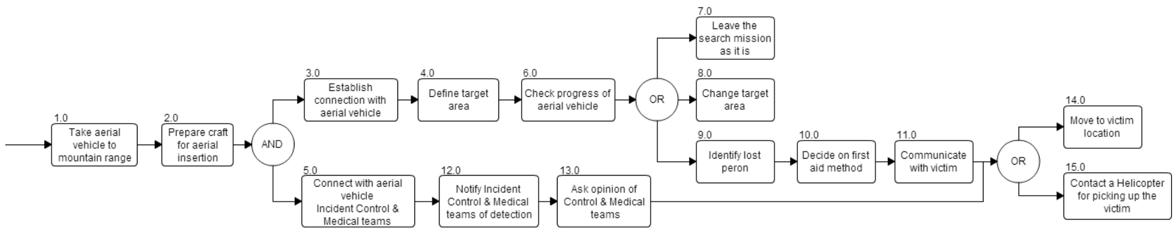


Figure 3.3: Functional Flow Diagram of the Ground Unit

3.3 Project Statements

Using the Mission tasks and goals, as presented in Section 3.1, the following Project Statements are defined.

Mission Need Statement
The Search and Rescue operation needs to be faster, safer, cheaper and more effective than existing solutions.

Mission Statement
Nora will provide aerial support to Search and Rescue teams while reducing the risk and the cost of the rescue operation and increasing its effectiveness.

Project Objective Statement
Design an aerial support system to assist ground Search and Rescue teams for high-mountain Search and Rescue missions, with an operational cost not exceeding €1650 per hour with a team of ten students in ten weeks time.

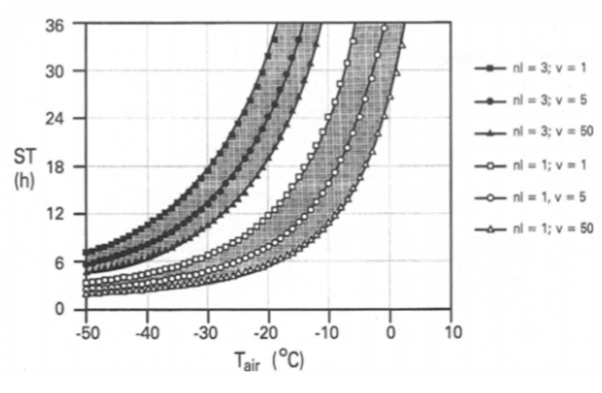
3.4 Stakeholders

When analysing the problem, it is of key importance to identify several parties with interest in the realisation of *Nora*. These parties are also known as stakeholders. This section sets out to evaluate their needs and desires, so they can be implemented into the design process. Each stakeholder is given an abbreviation used in the identifier of the stakeholder requirements. In subsections 3.4.1-3.4.3, the different stakeholders with their interests in *Nora* were stated and divided into primary, secondary and other stakeholders.

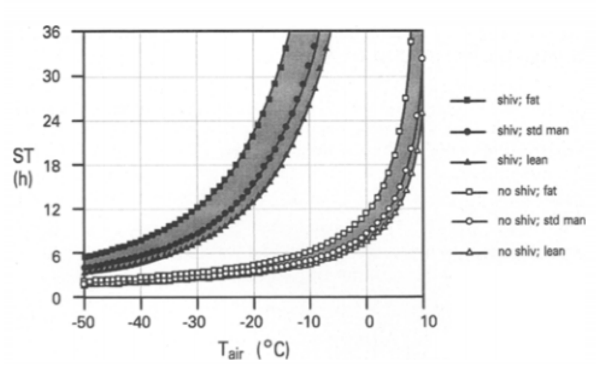
3.4.1 Primary Stakeholders

Primary stakeholders are those that influence the requirement analysis most and are key in the final design characteristics.

Missing Person(s) (SH1)
This is the person lost and/or injured in mountainous terrain. The missing person wants to be rescued as fast as possible and to feel taken care of. To understand the behaviour of the missing person(s), more research has been done regarding the survival rate of the missing person(s). By using a theoretical model, a relation between the prediction of survival time and the air temperature can be shown in Figure 3.4. [4] This model can be used to make a prediction for the first hours of the search. As time proceeds during the search and rescue mission, many other factors will play a role, e.g. attack by wild beasts and starvation.



(a) Windspeeds (v) from 1 to 50 km/h and different numbers of clothing layers



(b) Windspeed of 5 km/h with two layers of clothing in a loose configuration for body types ranging from lean to overweight

Figure 3.4: Survival Time (ST) vs Air Temperature (T_{air}) as predicted by the model [4]

As an example, research has been done in the State of Oregon (United States of America) [5], which can be used to give a general impression of a full data set on missing persons and SAR-missions. As can be seen in Figure 3.5, the first phase of the search is crucial, since the chance of survival is largest. This clearly shows that the missing person has a need for shorter search times and thus the implementation of *Nora*. Furthermore this information can be used to design the different stages of the search mission.

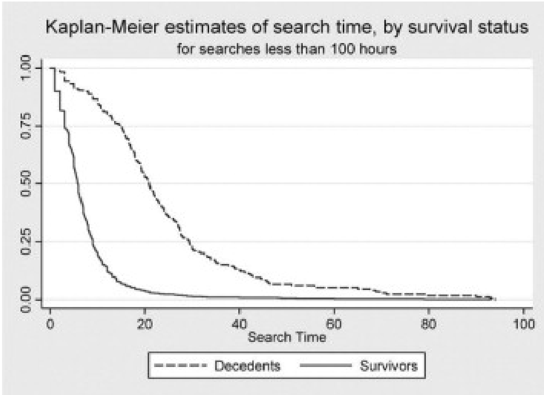


Figure 3.5: Search Time and Survival Rate in the State of Oregon [5]

Also, the human machine interaction of *Nora* does not limit itself to the person controlling the system. Although realistic interaction is not necessary at first, interaction between the rescue team (including the medical team) and the missing person(s) are important during the rescue phase after search. [1]

Searcher(s) (SH2)
These are the rescuers on foot or in a helicopter (or other device) that go out to search for the missing person. The primary interest of the searchers is that *Nora* can provide more information about the missing person, preferably the location, so the searchers can work to the point. SAR missions could put the search members in very dangerous situations, whilst rescuers do not want to endanger their own life. Therefore searchers want *Nora* to be safe to use and that it can be used to search in areas where the searchers can not come (safely). Also if *Nora* can shorten the search time, the searchers are exposed to the dangerous circumstances for a shorter time period. Furthermore they want *Nora*'s system to be easy in use, so it can be used without special training.

From Section 4.1 it also followed that there is the desire for the drone to be light weight, so it can be taken along easily. From *High Altitude Medicine & Biology* (Elsensohn et al., 2011) it is found that the first responders carry backpacks which range from 5 to $8kg$.[6] It is assumed that the absolute minimum of a first response team is three persons due to their own safety. For the drone there are now two options. Nora's system could therefore be $8kg$ maximum, carried by one man, while the other two persons carry the needed water, food and equipment. The other option is that the drone would be separable. The weight of the drone could now be split over the three persons. Assuming they have to carry $2kg$ of water, food and equipment per person for themselves, this leaves $6kg$ for the drone. Therefore the separable system could weigh up to $18kg$.

For the development of operation types it is necessary to understand the capabilities of the SAR team. Three of these SAR team characteristics are the walking speed of a single searcher, the team size and number of search operations. To determine the walking speed of the SAR team, the Naismith rule or the Tobler rule can be used [7]. These functions describe the walking speed versus the slope of the path. Both rules can be scaled by the fitness of the person, therefore this rule can also be applied on the missing person(s). An estimation of travelled distance is already given in the baseline report [2]. The base speed of the person is different for both rules, but still the horizontal speed when searching is not likely to exceed $5km/h$. The team size varies a lot, logically a search operation can be performed by one person, but large search operations covering large areas can go up to dozens of searchers. Number of search operations also vary a lot, especially with jurisdictional area. The Malibu SAR team is appointed

[1] Interaction, URL `http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1291662`, [cited 17 May 2015]

to cover an area of $484 km^2$ and performed 491 missions in 2013, followed by 597 missions in 2014 [2]. The ability to detect something or someone by a searcher is determined by the swath width. Research has been done to investigate the searching ability in varying seasons and on various locations in the United States. It can be used to make an estimation of the swath width of the searcher. Effective swath widths range from 8 meter to 142 meter depending on season and environment [8]. To estimate the usage of the system and the relative performance to current search performance, these numbers can be used.

One of the contacted SAR teams was happy to make their operating area available to test the system. This can be a really beneficial method to test the system, however it might also be possible to test the system at a dedicated training facility. Multiple educational facilities exists, such as the Bergwacht-Zentrum für Sicherheit und Ausbildung[3] in Germany, with a dedicated indoor training facility for helicopter usage and the Centro de Adiestramientos Específicos de Montaña of the Guardia Civil, responsible for education of mountain service personnel[4]. Besides these dedicated training sites, many SAR teams have their own training sites to train their own searchers. Keeping all this in mind, it could be very helpful to keep in contact with all the contacts for later stages of design.

Customer(s) (SH3)
The customers are the buyers of *Nora*. They want the device to be cheap and still have a long durability. Furthermore the device should be easy and cheap to maintain. Also it has to perform its task well, otherwise it will not be a good investment for the customers. Additionally they want *Nora* to fall within regulations, otherwise they can not use it. The main customers are the organisations that are in possession of the gear. It is therefore possible that the customer is different from the main organisation of the SAR team. Other potential customers are described in the form of other markets in Section 4.2.

Although different SAR teams have different cost budgets and organisational hierarchies, our objective is to make the system widely available. Therefore it is important is to know what their cost budget is. In the market analysis of the *Baseline Report* [2], a comparison with the operational costs of a helicopter was made. To account for potential customers that are not able to make use of current solutions for aerial assistance such as a helicopter, a different cost budget is defined in the form of a purchase price. The local sheriff's department of Jackson County for example has $5,000 available for the acquisition of a multipurpose drone, which is able to carry an IR camera and package. [5]. Since the objective of flying in harsh mountainous conditions is a large added value to such a system, the price of the system can be significantly increased.

3.4.2 Secondary Stakeholders

Secondary stakeholders are those that influence the requirement analysis less than primary ones, and are hence less driving in the design characteristics.

Medical Teams (SH4)
These are the people that will provide medical assistance and advice in the case the missing individual requires medical attention. These people will need to have proper communication with the patient to make a correct decision. A communication link is therefore essential for this stakeholder.

Local Population & Visitors (SH6)
These are the people in *Nora*'s operating area for living, work, vacation, day trips etc. First of all the device should be save also for these people, including safety of health. Furthermore, the noise of *Nora* should be limited to avoid annoyances.

Local Authorities (SH7)
By local authorities the instance that is responsible for the local authority is addressed. This instance wants that it is able to follow the actions of the device for control if necessary.

[2] Malibu SAR team, URL `https://www.facebook.com/MalibuSAR`, [cited 20 May 2015]
[3] Bergwacht-Zentrum, URL `http://www.bw-zsa.org/?id=331`, [cited 18 May 2015]
[4] Guardia Civil, URL `http://en.wikipedia.org/wiki/GREIM`, [cited 18 May 2015]
[5] Jackson County Sheriff's Department drone budget, URL `http://lacrossetribune.com/jacksoncochronicle/news/local/drone-technology-on-the-way-for-sheriff-s-department/article_585771f9-a73a-5fea-982d-2b71fd0f115a.html`, [cited 20 May 2015]

Government (SH8)
The government has national regulations, which they want the device to follow. Also the government wants the system to be safe for all people.

3.4.3 Other Stakeholders

Numerous other stakeholders that are less directly involved in the design characteristics process are outlined below.

Missing Person's Family & Friends (SH9)
The family and friends of the missing person want the missing person to be found as soon as possible. In the mean time they want regular updates on how the SAR mission is going. They want to have confidence in *Nora*.

Property Owners (SH11)
Property owners are the owners of land above which *Nora* is operating. They want to ensure their privacy, but due to the purpose of the mission, the main stake property owners have is to ensure their property will not be damaged during the SAR mission.

Engineering Company (SH12)
With the engineering company is meant the group of engineers responsible for the design of *Nora*. For the engineering company it is very important to stay within the cost and time budgets as their main interest is to make profit. Also it is of interest that the device could be easily adapted for other applications, so the market is kept as broad as possible.

Manufacturer (SH13)
The manufacturer is the instance or person responsible for the production of *Nora*. The main interest of the manufacturer is to make profit as long as the system is safe to manufacture. One possible way is to produce sustainable, so waste in the broadest sense of the word is reduced.

General Public & Media (SH14)
The general public are the people that have nothing to do with the operation of *Nora* directly, but hear, read, write and talk about the device. It is important that the general public is positive about the device instead of sceptic. If *Nora* has no positive image, it will influence the customer's trust in the product. This can for example be done by creating positive press releases on sustainable development or privacy maintenance.

4 | Market Analysis

The market has great influence on the product design as the ultimate goal is to sell the product. Based on the mission goals and statements described in Chapter 3, a market analysis is performed. This analysis is extensively described in the *Midterm Report*, and a brief summary can be found in this chapter. Firstly, the primary market is analysed in Section 4.1, followed by an elaboration on the discovery of other future potential markets described in Section 4.2. Finally the volume and achievable share of the market is estimated in Section 4.3, which will be used for the return on investment calculation in Section 10.8.

4.1 Primary Market

As indicated in the project statements in Section 3.3, *Nora* will provide aerial support to mountain SAR teams. The design will therefore be focused on this market. The mountain rescue teams with specialised operators all over the world operate with the same objective; to safely return lost or injured mountaineers and other visitors. In this section, information will be given about the structure of these mountain rescue organisations, followed by an elaboration on the current operation execution. Subsequently the current state of technology, future predictions and an example of a competitor will be described. Finally, due to the killer requirement *MH-SH3-04* stated in Chapter 5, an elaboration on the regulations will be done.

4.1.1 Organisation

The way SAR teams are organised differs significantly. The responsible parties however can be roughly categorised in two groups: governmental authorities and private operators. Governmental authorities can be nationwide departments, as in Spain or Italy, or local police departments, as in New Zealand. The local police, however, works in cooperation with private operators consisting of volunteers as they are often smaller. Either way the authorities are supported and organised by the government. Therefore their financial budgets are larger than private or voluntary organisations, which is positive for using highly specialised or expensive equipment such as helicopters and well-trained mountain rescuers. Contradictory some nations have private operators, as in the United States and Nepal. These private operators are much smaller than the governmental authorities and are often focused on a local area. Therefore they may require additional assistance from governmental authorities. Private operators often lack the ability to attract sufficient funds, therefore sometimes these private operators consist mainly of volunteers, as in England and Wales. This information will be used for the market estimation in Section 4.3.

4.1.2 Current Operation Execution

Mountain rescue missions are rarely identical due to the fact that the incidents are subjected to circumstances. Even so, in order to get the operation up and running fast and effectively, guides exist that define required actions during planning and execution phases [9]. Planning of the mission starts immediately after an incident has been reported to the responsible authority or team. They start with obtaining the missing person's point last seen (PLS) or known (LKP). Additionally, the urgency should be determined to establish the necessity and intensity of search, including deployment of available crew and equipment. This is dependent on the missing person's age, health, available equipment and weather conditions. Then the mission is set into motion. Planning and execution mostly overlap from this point in time, since investigation during the mission may lead to different mission profiles due to more detailed subject characteristics or tracking results. The PLS or LKP forms the starting position for the search parties as they start scanning territory with a high probability of area (POA). The intention of a missing person to visit the mountains affects the search strategy significantly. From past search operations it can be seen immediately that enormous differences in radii of missing persons for a theoretical guarantee of detection exist. Children aging up to six years old are almost always found within three kilometers, but they are very hard to detect, because they tend to hide and do not respond to signals by rescuers. On the other hand hikers travel furthest and could be found within a radius of 25 kilometers if lost for one day. Hikers, however, will try to find trails or other lines of least resistance. This can be used for searching strategies to narrow down the large searching area [10]. In general, search and rescue teams try to obtain as much information on the missing person as possible to construct a search pattern that is most effective for that specific incident. The information in this subsection will be used for the mission design described in Chapter 7.

4.1.3 Current State of Technology

Nowadays search and rescue teams consist of units on foot in some cases assisted by aerial vehicles. Aerial vehicles can cover much more area due to the elevated position. At this moment helicopters are the most deployed type of vehicle, but due to high costs ($3300 per hour) they are still only deployed for extreme incidents [11]. In England and Wales, only in 6% of the cases helicopters were used to assist ground units in SAR missions [11]. These helicopters contain multiple sensors (often Multi Sensors Systems, board Forward Looking Infrared or Night Vision Goggles [12]) that enable pilots to enhance their visuals and help to identify targets. Helicopters are however limited in operations by the weather, visibility, performance and the advanced instrument drawback. Furthermore clouds at low altitudes, strong winds and traitorous gusts across ridges can seriously endanger the helicopter crew's lives. The performance is mainly dependent on the amount of fuel taken along and the situation the helicopter may find itself in [12]. Often less fuel is taken on board, to maximise the power margin, however this shortens the endurance, which results in a huge drawback in the downtime. Although highly advanced, modern instruments have reduced effectiveness in warmer environments [12]. A major drawback is the emission of energy by non-living substances. Rocks and cliffs absorb and re-emit thermal energy and cause the contour of a living object to blend in with the surroundings and therefore makes it difficult to register them.

4.1.4 Future Prediction

From market research, it is known that more and more SAR organisations have been seriously looking into drones. If they were to use drones, it would have been for the search of missing persons and mountaineers struck by avalanches, says a spokesman of Bergrettung Tirol. An interesting desire is that the drone has to be small, light weight and easy to use by rescue operators. It will be deployed in parts where cars cannot reach or operators cannot get to on foot. Mainly due to this need, the drones should be easy to take along and so the requirement arises for a drone that is both not too big and not too heavy. This information is considered for the design described in Chapter 9.

4.1.5 Competition

Despite some modular UAVs designed for extreme conditions as the *Aeryon Scout* are available on the market, no direct competition of *Nora* can be found. Based on the initial requirements, *Nora*'s endurance will be 4 times higher than the *Aeryon Scout*. *Nora* is also able to operate in more extreme conditions with a larger operating temperature range and higher wind tolerance. Although it has to be said that the *Aeryon Scout* only weighs around $2kg$. [1] To provide an indication of the market price of the closest competitors, Deputy Chief Gary Conn states that an upfront price of $108700 is paid by the Police Service in Ontario for the *Aeryon Scout* and its annual operating costs. [2] This information will be used for the market price calculation shown in Subsection 10.8.2.

4.1.6 Regulations

When designing an aerial vehicle, the aviation authorities always come into play. The product is intented to be used in various countries for search and rescue, each with their own aviation authority. In the United States, the Federal Aviation Administration (FAA) defines different allowance for different applications. A SAR drone would fall under the public operations regulations for which more lenient restrictions are applicable and therefore no regulatory obstacles are foreseen. In Europe every country has its own aviation authority. However the European Aviation Safety Agency (EASA) has set-up some governing regulations every country has to follow. EASA is currently in the process of drafting new regulations which are very open and will pave the way for drone integration in the current aviation regulations. The currently proposed regulations by EASA provide a large degree op freedom for Unmanned Aircraft System (UAS) operations in the future[3]. Therefore also for Europe no regulatory obstacles are foreseen, despite the fact that current regulations are very restrictive. For example, the regulations in

[1] Aeryon Scout, URL `http://aeryon.com/aeryon-scout`, [cited 29 June 2015]

[2] Aeryon Scout Police Service Ontario, URL `http://www.uasvision.com/2013/09/20/police-service-in-ontario-to-get-aeryon-scout/`, [cited 29 June 2015]

[3] EASA regulations, URL `http://www.forbes.com/sites/gregorymcneal/2015/03/23/european-drone-regulations-are-about-to-get-smarter-and-more-permissive/`, [cited 27 April 2015]

Spain require that a UAS over $2kg$ and up to $150kg$ requires to stay within line of sight at all time, which is defined as $500m$ horizontally and $120m$ vertically. Also no autonomous flight is allowed at the moment[4].

A promising market could be Nepal, as there are very high mountains, e.g. the Mount Everest. The recent earthquake proves the importance of effective SAR missions. Nepal does not have any regulations for small UAS[5]. In New Zealand there are also no restricting regulations on UAS operations as long as an exemption is granted by the Civil Aviation Authority of New Zealand[6]. In general it can be said that the current regulations can be very restrictive in some countries. Aviation authorities are looking for a safe way to integrate drones operations into society. Regulations are still under development and the progress is promising for the application of a SAR UAS.

4.2 Secondary Market

The the opportunities for UAV's are endless. UAV's can add value. Let it be efficiency in operations, e.g. faster and cheaper operations compared to helicopter usage, or revolutionize industries, e.g. local delivery of packages via the air. *Nora* with her ability to operate in mountainous areas, does not limit her applications to professional search and rescue operations. There are multiple applications where *Nora* has significant advantages over competitors due to the lower altitude ceilings of other UAV's. Some applications are worth mentioning since they have similar objectives or other benefits by using a UAV with these proposed capabilities. These other markets are listed below and describe what their potential benefits are. Besides that, it is described what should be changed in the configuration of *Nora* to achieve this.

Research in Mountainous Areas
With the large range of sensors that can be used on *Nora*, the system will be able to observe numerous phenomena in mountainous areas. Due to the different types of search operations, she can be used for research in various fields, e.g. biological research such as wildlife migration and environmental research such as mapping local temperature differences. Possible changes to the sensor configuration and processing system can be made to achieve this.

Mountain Associations
A lot of mountain associations, not dedicated to SAR missions, can face the problem of missing one or more persons. These mountain associations can consist of organisations ranging from the local hiking club to a big ski resort with thousands of daily visitors. Making a low cost UAV would help to make it widely available and respond to an alert faster. Other types of operations can also be considered for these organisations, such as patrolling. To achieve this a lower purchase price and lower operational costs need to be considered due to the fact their willingness to pay is considered to be lower. Therefore, cheaper parts that might decrease performance could be considered to match their needs.

Urban SAR Teams
The main objectives state implicitly that the search area is inhabited or has a low number of inhabitants. In the case of a disaster in an urban mountainous environment[7], *Nora*'s usefulness based on the described objectives could be limited. Changes to the sensor configuration and processing system can be made to account for urban environment and larger search teams.

Other SAR Teams
The general concepts of an aerial assisted SAR operation can be adapted to more than only the mountain SAR teams. These other applications may require adaptations to the vehicle in all sorts of ways. For example, a maritime SAR UAV has to operate in a salty environment and has to be adapted for these conditions. Research can be done in the future to design for other applications.

Authorities and Military
Local authorities could make use of the system for detecting illegal activities in remote or hard to reach areas. These illegal activities can consist of drugs laboratories, dumping of toxic waste and lots of other

[4]Spanish regulations URL `http://www.twobirds.com/en/news/articles/2014/spain/spain-temporary-regulations-on-commercial-use-of-drones-approved`, [cited 24 June 2015]
[5]Nepalese regulations, URL `http://nepalitimes.com/article/nation/Game-of-drones,1329`, [cited 27 April 2015]
[6]Regulations of New Zealand, URL `http://www.caa.govt.nz/rpas/index.html#Outside`, [cited 27 April 2015]
[7]News, URL `http://www.un.org/apps/news/story.asp?NewsID=50802`, [cited 18 May 2015]

activities that can pose threats to the (local) environment. This application is considered to be achievable with the same hardware configuration as for the initial SAR mission. Besides that, a lot of military applications can be thought of considering *Nora*, such as aerial intelligence and dropping small packages.

Polar Missions
Nora will be able to fly at the Earth's poles. Although she will not be operable in all conditions[8], *Nora* might be used in optimal conditions to do research. Lower temperatures will require different sensors and possibly a different aerodynamic configuration. Future research can be done to make an adopted design that could help to increase the safety of polar missions, ultimately avoiding casualties. [9]

Aerial Imaging
A drone able to fly in mountainous areas could also be used for aerial imaging. Most probably the UAV should be low cost to be able to use it solely for this purpose. Although such a system can be used by professionals, this application will most likely be adopted by hobbyists. Therefore *Nora* should be compatible with existing cameras, as an extension of the imaging tools already available. Consumer drones are often priced below $1,200 where drones for hobbyists are ranging from $1,200 to $5,000[10]. Although this does not describe operational costs, it is a first estimate for the cost budget of other markets.

Other Markets
For most of the other markets, problems could arise with the regulations as they are less strict for rescue missions. However, because these regulations are already being adjusted for such rescue missions, in the future these regulations might also become less strict for these other markets.

4.3 Market Estimation

In this section, the market volume is estimated, followed by an indication of the achievable market share for the next 7 years.

Market Volume
The market volume was estimated using the only available open source database *Search and Rescue Contacts World-Wide* [11]. Due to the expensiveness of the product, it is assumed that only countries with an high average national income were filtered out of all the world's 214 countries, using the *World Bank national accounts data* and the *OECD National Accounts data files*[12]. For the resulting 75 countries, 297 organisations were determined to be potential primary customers. Despite the fact that the database is not complete for all of these 75 countries and some of these organisations do not have a mountain SAR function, it is the best usable source available and it is assumed that the incompleteness for some countries will compensate for the non-mountain SAR organisations listed in this database.

Achievable Market Share
It is assumed that all the 297 organisations will possess 2 *Nora*s meanly at the end of 2022. In 2015 and the beginning of 2016, prototypes will be used to test the success of *Nora* during several missions, but the production will start at the end of 2016 when the first *Nora* will be sold. After successful completion of several missions of *Nora*, more organisations will be able to test the device. From 2018 onward, an exponential grow is expected to finally reach an expected total of 594 *Nora*s sold at the end of 2022. The estimations for the achievable market share for the upcoming 7 years are shown in Table 4.1.

Table 4.1: Estimated Market Share

	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Produced	0	1	5	20	31	67	148	322
Total on market	0	1	6	26	57	124	272	594

[8] Weather conditions, URL `https://icecube.wisc.edu/pole/weather`, [cited 18 May 2015]
[9] Arctic Mission, URL `http://www.nltimes.nl/2015/04/30/dutch-arctic-researchers-missing-in-canada-distress-signal-sent/`, [cited 10 May 2015]
[10] Drone Price, URL `http://www.macon.com/2015/05/13/3744032_startups-seek-footing-in-burgeoning.html?rh=1`, [cited 20 May 2015]
[11] International SAR agencies database, URL `http://sarcontacts.info`, [cited 29 June 2015]
[12] World Bank, URL `http://databank.worldbank.org/data/home.aspx`, [cited 23 June 2015]

5 | Requirements

This chapter states the most important requirements defined for the designed UAV, *Nora*. During the Midterm Phase, killer, driving and key requirements were identified. These requirements are listed below. The full list of requirements and their explanation can be found in the Midterm Report and the compliance check of these requirements is shown in Section 10.5.

Killer Requirements

- MH-SH3-04: The system shall comply with regulations of the aviation authority in the customer area of operation.
- MH-SYS-04: The system shall be able to deploy a first-aid kit within a radius of $0.3m$ from target location.
- MH-SYS-15: The system shall include detection systems that can locate missing persons.
- MH-SYS-27: The system shall have a communication range of $50km$.
- MH-SYS-29: The system shall be able to loiter in a given area.
- MH-SYS-30: The system shall be able to search a given path.
- MH-SYS-31: The system shall be able to search a given area.
- MH-SYS-32: The system shall be able to focus on a given point.
- MH-SYS-ELE-COM-03: The data rate shall be at least $7.5MBit/s$.
- MH-SYS-OPS-FA-01: The first-aid subsystem shall deploy a first-aid kit with an accuracy of $0.3m$.

Driving Requirements

- MH-SYS-19: The system shall be able to withstand winds of up to $80km/h$.
- MH-SYS-20: The system shall be able to withstand gusts of up to $100km/h$.
- MH-SYS-35: The system shall have a real-time video link with a mobile ground unit.

Key Requirements

- MH-SUS-01: At least 70% of the structure shall be bio-based, re-used or recycled at the end of the aircraft service-life
- MH-SYS-01: The system shall consist of at least one unmanned aerial vehicle.
- MH-SYS-02: The system shall be able to locate at least one lost person.
- MH-SYS-03: The system shall be able to provide first aid help to at least three missing persons.
- MH-SYS-07: The system shall be portable by man on foot walking on the mountain.
- MH-SYS-08: The system shall be operable at sea-level ($0m$) to $5000m$ altitude bounded by a latitude range of $S35°$ to $N65°$.
- MH-SYS-09: The system shall be operable at temperatures ranging from $-40°C$ to $60°C$.
- MH-SYS-10: The system shall have an endurance of at least two hours.
- MH-SYS-13: The unmanned aerial vehicle shall have a span of no more than $1.5m$.
- MH-SYS-14: The system shall have a weight lower than $18kg$.
- MH-SYS-39: The operational cost shall not exceed €$5/h$.
- MH-SYS-ELE-DAT-01: The data handling subsystem shall store its measured data for $120min$.

6 | Conceptual Design

This Report describes the final design of *Nora* and all her functions. Before arriving to this point in the design, multiple concepts were conceived in order to find the best possible design. This chapter will shortly summarise the steps taken in the design process during the Baseline and the Midterm Phase. Section 6.1 shows the design option trees that were created. The trade-off of these design option trees can be seen in Section 6.2. Then the operational concepts thought of in the Midterm Phase can be found Section 6.3. Taking the operations into account, different design concepts were generated, see Section 6.4. The trade-off of these concepts can be found in Section 6.5. The chosen concept was further developed using expert's opinion within the Aerospace Engineering Faculty of TU Delft. This process can be found in Section 6.6 together with a mass budget estimation.

6.1 Design Option Tree Generation

As a first step towards generating a feasible design, the design possibilities have to be defined. In order to do this in a structured way, multiple design option trees were set up. A design option tree is a visual way of listing all the options possible. In the Baseline Phase, a separate design option tree was created for the configuration of the aerial vehicle, the detection method, the package delivery procedure, the take-off procedure and the energy supply. This was done because it was not possible to list the enormous amount of options possible in one design option tree. In Figure 6.1, 6.2 and 6.3, the configuration design option tree, the detection and operation design option tree and the energy supply design option tree can be seen, respectively. The configuration design option tree tries to give an answer to the question how *Nora* will fly. In this design option tree all the possible ways to fly are listed. The detection and operation design option tree is a AND tree on the first level. The tree lists all methods that could be conceived for the search method, the take-off and landing method and the package delivery. The energy supply design option tree lists all possible energy supply methods that were thought of.

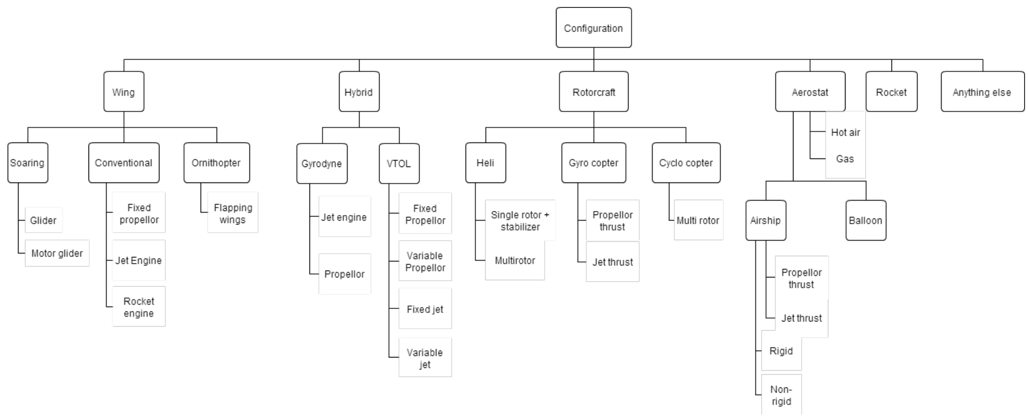


Figure 6.1: Configuration Design Option Tree

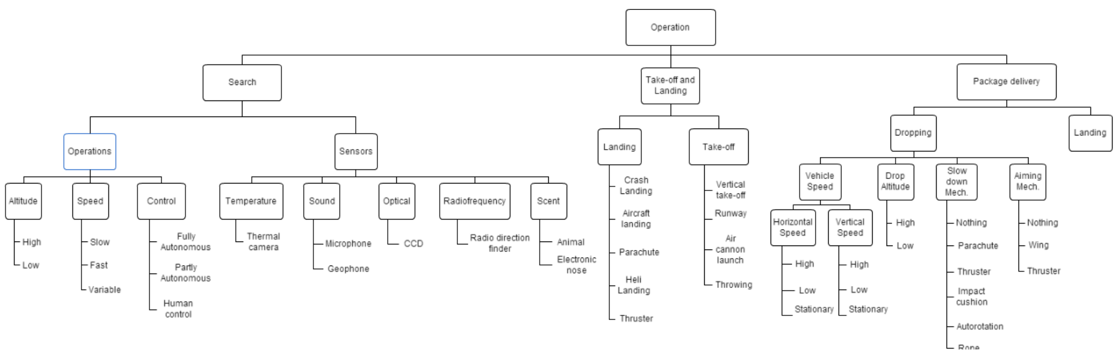


Figure 6.2: Detection & Operation Design Option Tree

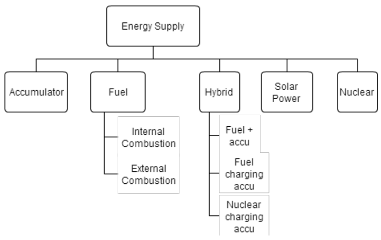


Figure 6.3: Energy Supply Design Option Tree

6.2 Design Option Tree Trade-off

As a next step in the design process, the different options thought of within the different design option trees had to be combined. However, due to the great number of combination possibilities, it was decided eliminate the unfeasible options per design option tree. This was done by means of a Strawman Elimination, followed by a trade-off process for the configuration and detection sensors.

The Strawman Elimination was conducted in order to separate the feasible designs from the non-feasible ones. The elimination is the crudest form of filtering out non-options and was used to create a backbone for subsequent feasibility analyses. The Strawman Elimination is based on four main observations. These observations are together with an example for each category enumerated below.

1. **Obviously Non-Concepts:** *Concepts named for the sake of completeness, but for which no immediate application is present.* Example: The rocket configuration. It could be dangerous for the SAR team to launch the rocket especially since the launch site has to be set up by themselves within the mountainous terrain. Furthermore a rocket is not able to perform the search operations as they were described in the Mission Design (Chapter 7).

2. **Non-Feasible Options:** *Concepts that are absolutely non-physical or are simply not practical at all.* Example: The Solar Powered Energy Supply. *Nora* also has to be operable in bad weather conditions, since more people get lost or injured during bad weather circumstances. During these conditions not enough sunlight is present to generate the needed amount of energy.

3. **Lacking Technology:** *Concepts that lack immediate applications because of a technology gap.* Example: The Cyclocopter. The cyclocopter is a concept that has only proven to work for a very short amount of time. The current working applications are used within doors and can not cope with wind gusts in the mountains.

4. **Sustainability:** *Concepts that grossly violate the sustainability goals.* Example: Nuclear energy supply. The radioactive waste created when generating nuclear energy is largely debated subject. Due to sustainability requirements and the sensitivity of the subject, this option was deemed infeasible.

After performing the Strawman Elimination, a trade-off was done for the configuration and the detection method. The selection of the best option in the other subjects, presented in the design option trees in Section 6.2, depended too much on the decisions made on the configuration and the detection method. Therefore a trade-off could not be made for these subjects separately.

For the selection of the configuration an analytical hierarchy process was performed. This means the correct weightings for each criterion and sub-criterion were given by comparing them pair by pair. Once this is done, a score for each design option to a criterion or sub-criterion is given which will then result in a total score for each design option. These scores can be compared to each other in order to find the best design option. In Table 6.1 the results of the configuration trade-off can be seen. It should be noted that this trade-off is purely for the configuration and does not take into consideration the combination with the other design subjects. The weighing criteria and a more detailed explanation of the process can be found in the *Baseline Report* [2]. In the table it can be seen that the four highest scoring configurations have been highlighted in green. These configurations are the conventional winged aircraft, the wing-prop hybrid, the single rotor and the multirotor. These are the four configurations that were still considered in the Midterm Phase of the project. This means that the others, that were highlighted in red, were discarded as not feasible for a high altitude search and rescue drone.

For the sensors a slightly different method is used because multiple sensors can be used in one design. Combining sensors increases the probability of detection and therefore it was not desirable to disregard sensors in this design stage. For this reason a more visual method was used to find the feasible sensors. A table was made where one can fill in all the scores for the different criteria. Each cell is then given a color which corresponds to the score in that cell. In that way one can easily see which sensors are better than the others. Sensors with a red cell for one of the criteria were rejected, because the selection of such a sensor would drive the design by an unacceptable extent. In Table 6.1, the sensor trade-off results can be seen. A more detailed explanation of this process can be found in the Baseline Report [2].

Table 6.1: Baseline Trade-off Results

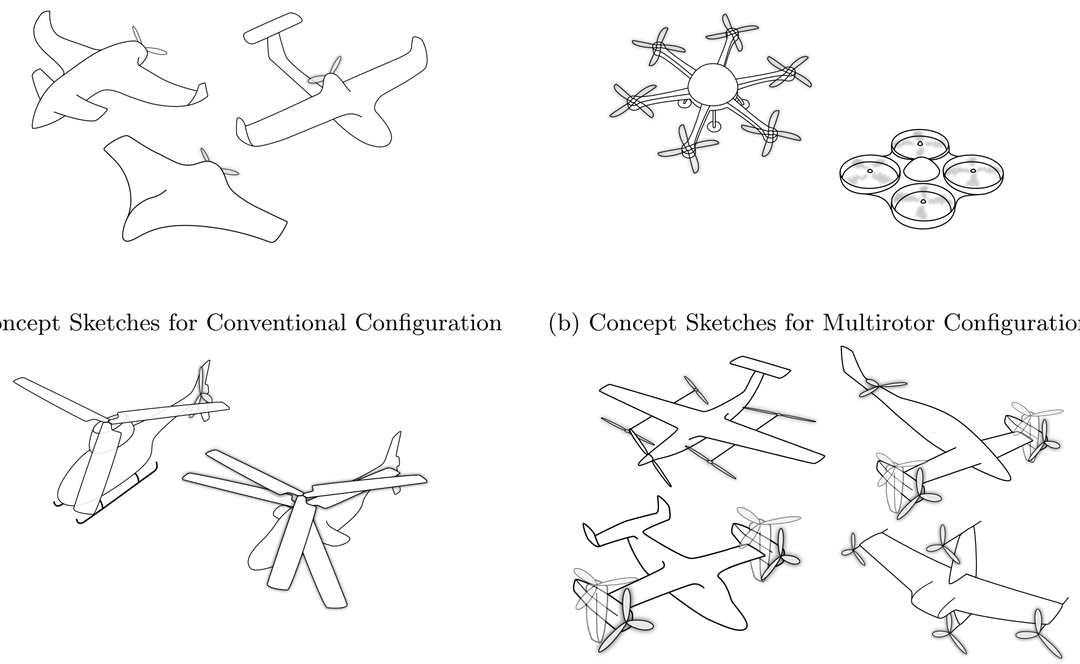
Configuration trade-off result

Configuration	**Result**
Convential winged aircraft	3.3
Motorized glider	2.9
Ornithopter	2.6
Hybrid (Wing-jet)	2.5
Hybrid (Wing-prop)	3.1
Single rotor	3.0
Multirotor	3.1
Autogyro	2.7

Sensor trade-off result

Sensor	**Result**
Thermal Camera	Accept
Optical Camera	Accept
Scent Sensor	Reject
Radio Frequency Antenna	Accept
Microphone	Accept
Geophone	Reject

To finalise the configuration initial trade-off, several concept sketches have been made for the remnant. These are to visualise the external layouts and the possibilities within a configuration category, see Figure 6.4.



(a) Concept Sketches for Conventional Configuration (b) Concept Sketches for Multirotor Configuration

(c) Concept Sketches for Single Rotor Configuration (d) Concept Sketches for Hybrid Configuration

Figure 6.4: Sketches for Remaining Design Configurations

6.3 Operation Concept Generation

After the preliminary trade-off methods described in Section 6.2 were performed, an analysis was done on the operation concepts. The operation greatly influences the mission and therefore also the design to be selected. After further researching the current existing operations, as explained in Chapter 4, multiple concepts which could fulfil this operation were thought of. One could distinguish the Single Drone System, the Dual Drone System, the Modular Drone System and the Drone Carrier System.

The Single Drone System would carry all required modules along and performs the search and package dropping on its own. The Dual Drone System splits the two main functions of the system over two drones, namely the detection of the missing person(s) and first aid package delivery. The advantage would be that the detection drone would not have to carry the 2 kg package plus the system for package delivery. Therefore the detection drone would be lighter and able to have a longer endurance. After detection the delivery drone can be sent to drop the package at the target spot. A disadvantage is the extra time that is required to the deliver the package after the lost person is located and the extra structural weight to be carried by the search and rescue personnel. The Modular Drone System was inspired by the Dual Drone System concept. Two modules are designed, of which one is installed on the drone at a time. There are two module types, one for detection and one for delivery. First a detection module can be attached, which has multiple sensors needed for efficient searching. Then it can be interchanged for the package, once the victim has been located. This means that the structure can be designed for less loads as it never has to carry the package and the full detection system. Lastly a Drone Carrier System was analysed. This concept uses one large drone, with multiple small drones that can detach. The large drone would fly at high altitude. The thermal sensors on this large drone could detect potential missing individuals. When the drone has detected something it could detach one or more smaller drones which would descend to identify the individual to check for false detection. A large advantage is the large area coverage that can be achieved. A drawback is the size and complexity of system.

After carefully comparing the operational concepts, it was concluded that the Single Drone System was the best option. The two drone system was discarded due to inefficient mass use and the drone carrier system was discarded because of cost and risk considerations. The fact that the drone had to return to the search and rescue team to obtain the package was considered to be unfavourable in the Modular Drone System. However it was decided that when using Single Drone system it is possible to fly the UAV whilst the package is detached. This means that the search and rescue personnel is able to decide to not included the package to increase the endurance. Moreover multiple drones could be used simultaneously of which only one would have to carry a package.

6.4 Configuration Concept Generation

In the three design options trees (Figures 6.1, 6.2 and 6.3) a lot of options were listed in a visual way. After removing some of these concepts using a *Strawman Analysis* and a preliminary trade-off the remaining options had to be combined into one complete design. One possible way to come up with complete concepts was to combine all options with each other. Then one can eliminate impossible combinations to reduce the amount of options. Using a trade-off the best concept or concepts can be found. This method assures that the best option will be chosen but it has the disadvantages of creating nearly 50,000 options. Within the given time frame it was not possible to analyse all option and therefore another method was proposed.

The chosen approach was to analyse each design characteristic that had to be determined step by step and find the best option at that point. An example: one can start with determining the energy supply and find the best option for that configuration. Afterwards the shape of the rotors was determined and so on. This method is comparable to a steepest gradient method in optimisation. It implies that it won't be certain that the best option will be found, but at least a local optimum is found. Each of the configurations are taken as a starting point. When generating the concepts, a certain order in which the subsystems was determined. Other concepts were expected when the order of subsystem determination was altered. However it was found that even when the order was changed, the same design solution was found. Therefore four different design options were generated using this method, namely one for each configuration option. A brief explanation of each of these design options will be described in Subsection 6.4.1. For each of these configurations the power and propulsion method, the take-off and landing procedure, the detection method and the package delivery method were determined and extensively investigated. The written explanation of the investigations can be found in the *Midterm Report* [3]. However, some aspects of this analysis were altered after the Midterm Phase. The analysis of the detection subsystem was extended after this phase in the design process and can be found in Section 8.2 and the adjusted ideas on the package delivery can be found in Section 9.7. In the final configuration trade-off this was not the case yet and therefore the design concepts will presented as they were thought of during the Midterm Phase.

6.4.1 Design Concepts

Using the studies done on power & propulsion, detection method, take-off & landing and package delivery, a design option was generated for each configuration. As was previously explained altering the order in the design process did not have any influence on the output and therefore four different design concept were created. Below the final characteristics can be found per configuration.

- **The Conventional Wing Configuration** has a fully electric propulsion system. Due to its inability to hover a catapult was considered most feasible for take-off. Furthermore a parachute landing was chosen over the crash landing possibility. For the package delivery powered descent was deemed most feasible and a combination of a thermal and optical cameras, acoustics sensors and radio frequency sensors was chosen for the detection system
- **The Hybrid Wing-Propeller Design** has a hybrid propulsion system and is able to take-off and land vertically. For the package delivery method either powered design or rope descent was found to be most feasible depending on the terrain characteristics. The detection system also uses a combination of a thermal and optical cameras, acoustics sensors and radio frequency sensors.
- **The Single Rotor Design** uses a fuel based propulsion system and takes off and lands vertically. For the package delivery again both rope and powered descent were considered. The detection systems combines thermal and optical cameras, acoustics sensors and radio frequency sensors.
- **The Multirotor Design** uses a hybrid propulsion system. Just as for the single rotor design vertical take-off and landing was found to be optimal. Again one of two methods was used for package delivery, namely rope or powered descent. Just as for the other configuration thermal and optical cameras, acoustics sensors and radio frequency sensors are used in the detection system.

6.5 Configuration Concept Trade-off

The four possible design options presented in Subsection 6.4.1 were then combined into one large trade-off table, which can be found in Table 6.2. The table combines the criteria and their relative weights. The criteria are detection, delivery, safety, weather resistance, take-off & landing, risk, sustainability, cost and sensitivity. The explanation of the chosen weights on each criteria can be found in the *Midterm Report* [3]. The relative importance is determined using a analytical hierarchy process. Most important to note is that this drone will be both modular as well as separable. In this context, *modular* means that payload (packages & sensors) can be replaced by alternatives and *separable* means the drone can be taken apart for portability by the SAR ground team.

As can be seen using Table 6.2, the hybrid configuration was found to the most feasible design option. This configuration was taken along to the Final Design Phase described within this project.

6.6 Hybrid Configuration Design

After selecting the hybrid wing-propeller design as best design option, the amount of design possibilities was still extensive. Multiple configuration layouts were developed using experts opinion within the faculty. The following section will elaborate on the information gathered from these experts and the different hybrid design options that were thought of.

6.6.1 External Expertise

This subsection will describe the knowledge that was gathered by consulting external experts within Delft University of Technology. A short summary of their most import remarks and advices are listed below.

Table 6.2: Final Trade-off

Concept	Detection (22.3%)	Delivery (17.5%)	Safety (15.4%)	Weather resist. (13.8%)	T/O & Land (11.3%)	Risk (6.7%)	Sustainability (6.1%)	Cost (4.9%)	Sensitivity (2.1%)	Total
Conventional Aircraft	**2.33** – Good area coverage but poor manoeuvrability	**2** – Limited drop possibilities; horizontal speed the package needs to lose	**3.00** – Relatively unsafe for SAR crew at launch	**2** – Horizontal take-off not favourable in bad weather; large response to gusts	**2** – Heavy & powerful catapult launch required; parachute landing far from optimal	**4.27** – Low complexity, technology very available & large range after failure	**3.44** – Low emissions, noise & required energy; easy application of renewable materials	**5** – Lowest cost due to low complexity & proven design	**4** – Lowest sensitivity to mass & endurance variations	**2.66**
Hybrid (Wing-Prop)	**4.33** – Highest area coverage & good manoeuvrability	**5** – Large flexibility in delivery strategy	**3.43** – Safe to operate, relatively safe in package delivery	**3** – VTOL is weather resistant; in cruise large response to gusts	**4** – VTOL ensures large range of applicability	**3.10** – Complex system, but good development feasibility & large range after failure	**2.18** – Acceptable energy performance, intermediate pollution & average possibilities for renewable materials	**1** – Relatively complex, thus expensive system	**4** – Reasonably stable performance with mass and power variations	**3.71**
Single rotor	**2.67** – Low area coverage, good manoeuvrability	**5** – Large flexibility in delivery strategy	**2.57** – Relatively large chance of impact with large rotor at landing	**5** – VTOL weather resistant, best response to gusts	**4** – VTOL ensures large range of applicability	**2.67** – Intermediate complexity, good feasibility & very low glide range after power loss	**2.29** – Poor energy and emissions performance, good range of options for materials & good maintainability	**4** – Relatively low cost due to low amount of parts	**3** – Sensitive to mass & endurance variations	**3.58**
Multirotor	**3** – Low area coverage but excellent manoeuvrability	**5** – Large flexibility in delivery strategy	**3.43** – Safe to operate, relatively safe in package delivery	**4** – VTOL is weather resistant, good gust response performance	**4** – VTOL ensures large range of applicability	**3.02** – Excellent man-oeuvrability, intermediate complexity and failure consequence	**2.07** – Low performance on emissions & energy; acceptable maintainability	**3** – Proven design, but more complex than single rotor or conventional wing	**3** – Sensitive to mass & endurance variations	**3.61**

MAVlab

The MAVlab was visited to receive valuable feedback from engineers with experience with UAVs of comparable size to *Nora*. They advised to use as few moving parts as possible, because every motor adds mass and complexity to the design. Every gram that can be saved is important because the $1.5m$ wingspan restricts the size of lift producing surfaces. An aircraft sitting on its tail could be a good solution. In this way the rotors for vertical take-of can be used for both the take-off phase and the cruise phase. The engineers advised against using rotating engines, noting that the only good reason these are used in aviation is that passengers do not want to take-off nose-up. Since *Nora* will not be carrying any passengers rotating engines are not necessary, because they only add complexity. Rotating motors also have a high inertia, causing the rotational motors to be quite heavy.

Another proposed concept was a blended wing fuselage concept, because it has a large wing surface area to provide the required lift. With the limited wing span of $1.5m$ it may be hard to provide sufficient lift. For dropping, a 'drag' hover could be beneficial so no true hovering capabilities. In this way true hovering capabilities are not strictly required for dropping so power can be saved. Power should be both electrical and chemical. Electrical power is necessary to provide peak power when required and to hover, but chemical power is essential to meet the relatively long endurance. To save energy, the hover time must be limited as much as possible since it is very energy inefficient.

ATMOS

The engineers from Atmos were contacted regarding the stability of the vehicle. They said that stabilisation with only one or two rotors is very difficult. One would rather want three axis control, especially while hovering in wind. Therefore they would go for three or more rotors. Also they said that ducted fans (so rotors in the wings) react slower than rotors in free airflow. With wind and gusts fast reactions would be preferable. Furthermore they explained that turning engines are very difficult to implement and introduce large forces, which would therefore demand more from the construction than fixed engines. On the other hand $15kg$ for the drone is pretty heavy, so it would still be possible. They would not choose it themselves due to complexity. Lastly they explained that two hours endurance is long, so optimisation should peformed for the wing area. Also for this mission a body is not really needed.

6.6.2 Hybrid Design Options

In this subsection the different hybrid design concepts will be presented and explained. Only the special characteristics of the concept will be highlighted.

Hybrid Concept 1

The first hybrid concept can be seen in Figure 6.5. In this concept two main wings are used for horizontal flight and four rotors are used for vertical flight and hovering. The drone can thus function as a normal aircraft and a quadcopter. The rotors are inside the wing such that the drag effect of the rotors is reduced during cruise flight. The holes of the rotors will be covered during cruise flight such that the wing does not lose performance. Another propeller will be used for forward thrust which is attached to the front of the drone.

Hybrid Concept 2

A second concept that was considered, resembled the previous concept with one critical difference. The rotors were not placed inside the wings, but rather outside. These could be either on the side of the wing or behind it, to avoid disturbance of the airflow.

Hybrid Concept 3

The third hybrid concept is a blended wing body that sits on its tail. It has only 2 propellers, one on the nose and one in the back. These can be used for take-off and cruise when necessary. The back rotor can be folded in during cruise to reduce the drag. The package can be dropped by hovering or 'drag' hovering as was outlined by the MAVlab Engineers.

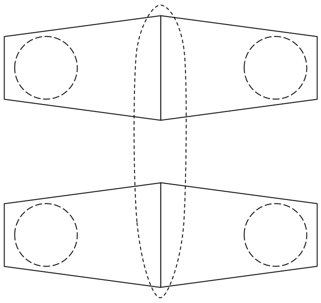


Figure 6.5: Hybrid Concept 1

Figure 6.6: NASA GL-10 Greased Lightning: a tiltwing example.

Hybrid Concept 4

The fourth concept is a tandem tiltwing aircraft with electrical powered engines, with an onboard generator to power up the batteries. Advantages of this design are the limited use of control surfaces. By rotating the engines with the wing, thrust vectoring can be used to steer and control the aircraft. The fuselage always keeps the same orientation, maintaining the nadir pointing and dropping capabilities during horizontal and vertical flight. Disadvantages are the control complexity because of the difficulty in transition between horizontal and vertical flight modes. The rotors will be over-designed in horizontal flight mode. The large force required to rotate the whole wing and the effect of a failing servo results in a non-operational state of the system. An example is shown in Figure 6.6. [1]

6.6.3 Hybrid Design Selection

Combining the knowledge of external experts with the design possibilities outlined in the previous subsection, a trade-off was made between the four remaining concepts. The criteria are taken from the previously mentioned expert knowledge. To come to a decision, each concept is ranked ++, +, +/−, − or −− depending on performance. The summary of this ranking, together with the reasoning behind it, is given in Table 6.3. The final decision is based on two factors. The pluses and minuses are added to a final score. Moreover, the lowest given score is taken along by its corresponding colour. A concept with any double minus score is deemed unfeasible, as the problems caused by this criterion are considered killing for the mission performance. From Table 6.3, it can be found that the concept of a tandem wing configuration with external rotors is elected as the optimal solution.

6.6.4 Mass Budget Estimation

When designing a UAV that has be carried into the mountains, it is of crucial importance to estimate a mass of all components to make sure the system does not become too heavy. For the market analysis (Chapter 6.6.4), it was found that first responders in search and rescue teams carry about $8kg$ and travel together with at least 3 search and rescue members. Therefore the total will be $24kg$. Assuming that each rescue worker has to carry $2kg$ of water, food and equipment for himself and taking a 20% contingency, this leaves $15kg$ for the whole *Nora* system. The three backpacks combined will weigh $3kg$ and the ground control system takes up $1kg$. This results in $11kg$ for *Nora*'s vehicle. In Table 6.4 the estimated mass budget can be seen, as it was determined using reference UAVs.

[1]NASA GL-10 Greased Lighting, URL `http://edition.cnn.com/2015/05/14/tech/nasa-greased-lightning-drone/`, [cited 24 June 2015]

Table 6.3: Hybrid Design Trade-off

Concept	Moving Parts	Stability	Payload implementation	Efficiency	Weather Resistance	Total
1	(- -) High amount of rotors, propeller coverage was highly discouraged	(+) Quadcopter /tandem combines 2 conventional layouts	(+) Body for payload and detection system	(+) Good efficiency with covered rotors	(+) No large wing surfaces exposed during TO/Land fro gusts	(++)
2	(+/-) High amount of rotors but no moving wings	(+) Quadcopter /tandem combines 2 conventional layouts	(+) Body for payload and detection system	(-) Exposed rotors create additional drag	(+) No large wing surfaces exposed during TO/Land for gusts	(++)
3	(++) Minimum rotors, no moving parts	(-) Difficult stability during vertical to horizontal transition	(- -) Very challenging to use payload during both hover as cruise, heavy package at the tail is unfavourable for cruise stability	(++) Flying wing is very efficient in cruise	(- -) Large wing area in wind direction during TO/Land, no control available	(-)
4	(- -) Rotating wings was highly discouraged due to its complexity	(+/-) Wing rotation for transition from hover to cruise is difficult in stability	(+) Body for payload and detection system	(+/-) Propellers cannot be optimized for both cruise and hover, reasonably efficient horizontal flight	(+/-) Vertical wings during TO/Land are unfavourable during windy conditions	(-)

Table 6.4: Estimated Mass Budget for *Nora*

Subsystem	**Mass [kg]**
Package	2.0
Package Structure	1.0
Structures	4.1
Power & Propulsion	2.0
Computer Systems	0.7
Communications	0.4
Detection	0.8
Total UAV	11.0
Tablet interface	1.0
Backpacks	3.0
Total UAS	15.0
20% Contingency	3.0
Food, water and Equipment	6.0
Total	24.0

7 | Mission Design

In this Chapter the mission will be described. Prior to making design choices, the design assignment at hand had to be properly analysed. First in Section 7.1 the operating conditions are explained, because in mountains wether and wind conditions can greatly vary and change easily in an instance. In Chapter 4 it was established that the mission will be different each time due to the behaviour of the missing person. To help achieve the set mission goals three different search modes were developed and can be found in Section 7.2. An operational diagram describing the system user operations is depicted in Section 7.3. The rescue workers will be able to select the desired search mode using a tablet. The interface for this tablet can be found in Section 7.4.

7.1 Operating Conditions Analysis

Before starting designing it is very important to demarcate the exact operating conditions in which it is needed to perform the mission. There are multiple aspects when covering the operating conditions. First the temperature and the vegetation are explained. Afterwards the wind is elaborated on.

7.1.1 Temperature & Vegetation

Mountainous terrains are very diverse in terms of weather and ground conditions. The drone must be able to fly from 0 to $5000m$ above sea-level. Because this $5000m$ is very high, only high mountain regions are looked at. In these high mountain regions there is an E-climate following the Köppen climate classification[1]. This E-climate is characterized by average temperatures below $10°C$ in all 12 months of the year. They often have to deal with large amount of precipitation, mostly in the form of snow. The ground is often frozen or covered by snow and sometimes even covered by glaciers. This E-climate is above the treeline. In this E-climate sudden changes in weather conditions are of frequent occurrence. Therefore the high mountainous terrain can be very dangerous. Additionally, the air is deflected by the mountains which can cause very strong winds with lots of turbulence. During a large part of the year, the ground is covered by snow and vegetation must renew itself every year, which is therefore not high. The ground in these high regions consists of very hard rocks that are occasionally covered with grass or loose rocks. Below the treeline (the height of the treeline depends on the latitude; the further north, the lower the treeline) the climate is influenced by the location of the mountain region. If this location is in a warmer and more moist climate, then trees will grow to higher length, compared to other locations and it will also be more bushy. In these mountain areas often caves or alcoves occur. If people would be trapped in one of these, it would be very hard to find and rescue them. It is also important to fly above the trees. The ten highest trees in the world are above $82m$, but in Europe the highest tree is $72m$. Also these trees are not found in mountainous regions, where the tree height is smaller. As can be seen in Figure 7.1 [2], the trees are up to $30m$ in almost all mountainous regions in the world.

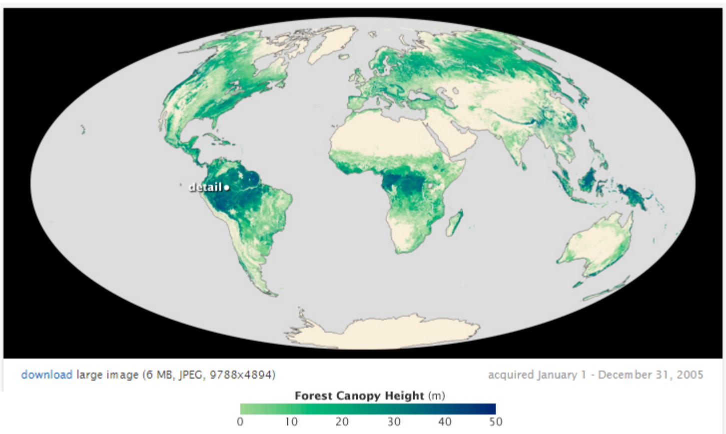


Figure 7.1: Tree Length Distribution on Earth

[1]Köppen Climate Classification, URL `http://koeppen-geiger.vu-wien.ac.at`, [cited 24 June 2015]
[2]Tree Length Distribution, URL `http://earthobservatory.nasa.gov/IOTD/view.php?id=77637`, [cited 13 May 2015]

7.1.2 Wind

Flying in mountains is different from flying in open country, therefore additional research is done on flying in mountains.

Wind Patterns
Mountains have their own weather systems. Interpolation of weather conditions between known points is therefore dangerous as rapid changes occur in mountains. Some rules of thumb can be noted when assessing wind conditions. Mountains have a windward side where the wind encounters the mountain and a leeward side where the air flows down over the mountain. On the windward side, favourable updraughts are present whereas on the leeward side dangerous downdraughts can be found. Downdraughts are often a source of turbulence. When crossing a valley, it is more efficient to fly on the windward side instead of in the centre of the valley due to the up-flow of air. As can be seen in Figure 7.2, downdraught should be avoided as much as possible. The demarcation line is where upddraughts change to downddraughts. Up- and downdraughts can also be created by the sun on a windless day. Air rises on the sunny side and descends on the shady side. This process is reversed when the sun sets.[13]

Another effect that can be made use of is the Venturi effect. In narrow valleys air is accelerated and wind speeds may double. This may also cause the local air pressure to drop, giving false altitude readings. A wave phenomena can also occur behind a mountain peak where air flow oscillates, see Figure 7.3. In the area below the peaks of this oscillation heavy turbulence can occur, resulting in loss of control, in clouds forming between the peaks icing can occur. Furthermore in general, flying near cumulonimbus clouds should be avoided as these produce heavy turbulence and icy conditions.[13]

Landing & Take-off
During landing, a descending approach is preferable over a climbing approach (approaching the landing spot from below). Sudden loss in lift or downdraughts can crash *Nora* in a climbing approach, because the power margin is not sufficient to escape. On a low power margin a wind disturbance can cause a rotor craft to tumble out of the sky, because there is no power left to correct[3]. When taking off it is preferable to climb away from the mountain.

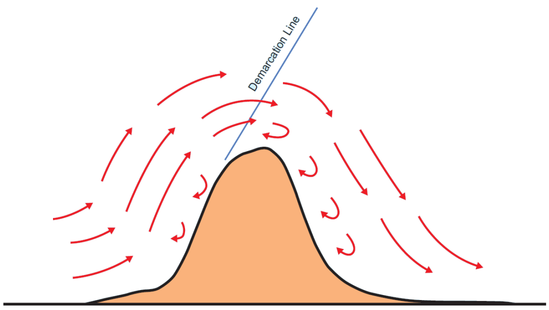


Figure 7.2: Up- & Downdraughts

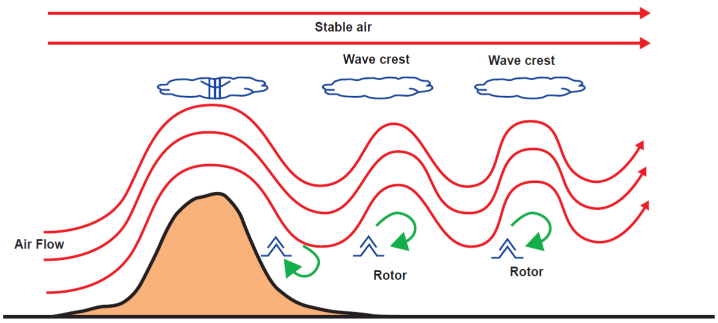


Figure 7.3: The Wave Effect

7.2 Vehicle Search Modes

For the operation to be successful, the chosen flight profile is of key importance. In the market analysis, as described in Chapter 4, research was done into the search modes of the search and rescue teams. Using the information obtained by this analysis of both the ground search profiles of different organisations and their thoughts on the UAV operation, different search profiles were thought of. In the following section three Search Profiles will be presented. Subsection 7.2.1 explains the altitude line search pattern, Subsection 7.2.2 the path search pattern and finally Subsection 7.2.3 the area search pattern.

[3]Wind disturbance, URL `Winddisturbancehttp://www.airspacemag.com/military-aviation/mountain-training-helicopter-pilots-180952127/?page=2`, [cited 13 May 2015]

7.2.1 Altitude Line Search

Constantly adjusting altitude, in order to avoid obstacles and remain at constant height above the ground as explained in Section 8.2, costs power and makes the mission inefficient. Therefore a method was developed to be able to fly using altitude lines. In order to determine such a flight profile, first height maps of mountainous areas had to be made. For this digital elevation data was used. In 2000 NASA performed their Shuttle Radar Topography Mission. This mission yielded high-resolution topographic data, which has been made globally available as of 2014. The highest accuracy available is $1arcsec$ which is approximately $30m$ depending on the location on Earth. Using the $1arcseq$ data height maps of the entire planet can be made. For a mountain area in which a specific search and rescue team operate, more accurate data could be implemented if this is readily available. [14, 15]

To determine the path along which *Nora* will fly, the rescue team can insert coordinates of the area to be searched. This will be done using the interface described in Section 7.4. First of all a 3D map of the area will be created as in Figure 7.4. Furthermore, two different plots will be created. One showing the area height in grey scale and one with altitude lines. The step size for which altitude lines will be created can also be varied by the rescue workers. Figure 7.5 shows a part the Dolomites, from just above Venice to the far west of Austria. Figure 7.6 shows part of the Himalayas in Nepal. For the contour map smaller regions are taken in order to be able to still distinguish the different altitude lines in one figure. For the two second maps that show the contour lines a resolution of $1800m$ by $1800m$ is chosen. Furthermore for the Dolomites, different altitude lines are distinguished every $15m$ and for the Himalayas every $50m$.

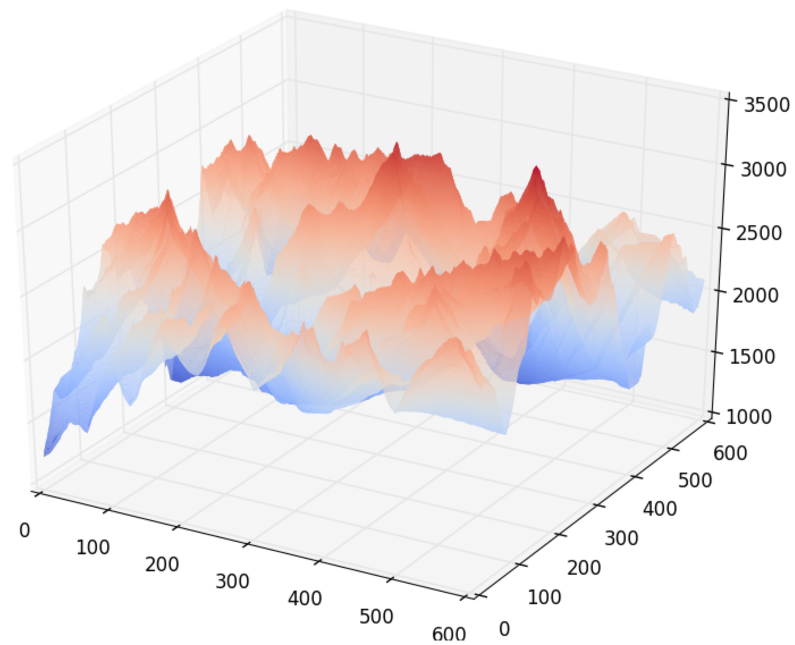


Figure 7.4: 3D view of the Dolomites (Distances Given in Meters)

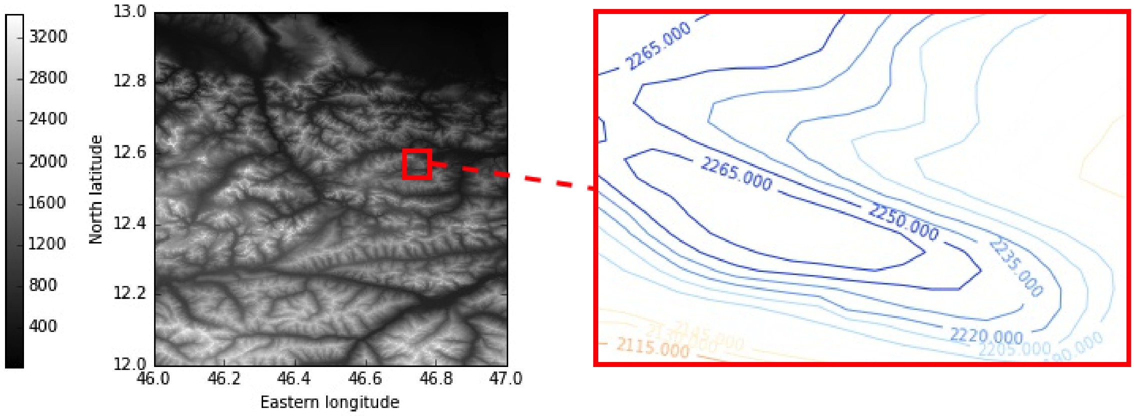


Figure 7.5: Height Map of Dolomites & Detailed Contour Line Map

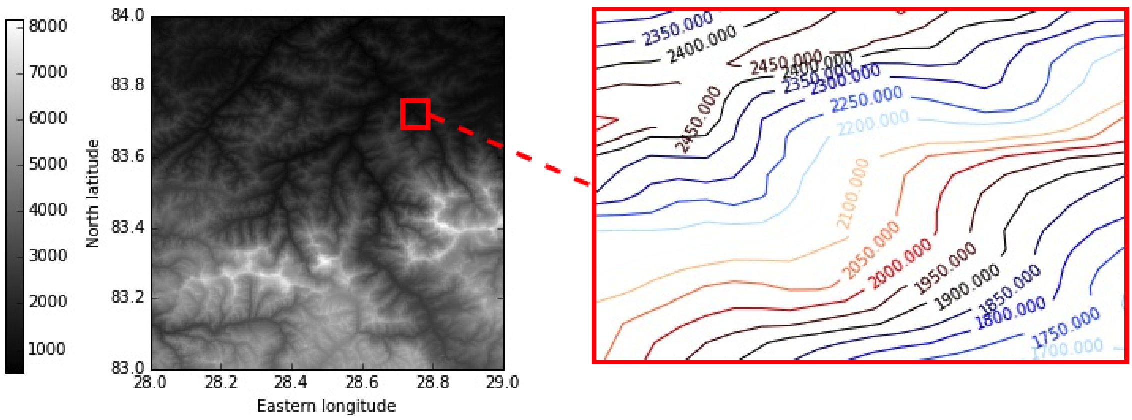


Figure 7.6: Height Map of the Himalayas & Detailed Contour Line Map

After inspecting the altitude lines of the search area using a tablet, the rescue worker is able to select a contour line, based on desired altitude. This can either be done on site, or the operations can be selected at the base station. Geographical coordinates of the chosen path are determined and can be implemented into the control system as described in Section 9.5. In order to avoid collision with mountains, the path has to be checked for turns that exceed the minimum turn radius. If this is the case the path will have to be adjusted. This technique will simplify the collision system that has to be designed, since the location of the mountain peaks has already been predefined. During the operation, the search altitude can be adjusted by the rescue worker. When doing so the height can be adjusted gradually, which is beneficial for the power consumption of *Nora*. The ground coverage is an important aspect to be considered in all search operations. When using this technique, one might have to fly back and forth on the same height a couple of times, adjusting its path slightly to assure full area coverage. After selecting the desired path an estimation of time it takes to follow the path and an estimation of the power consumption is made. This information is fed back to the search and rescue worker, who can then confirm the mission. After doing so the search process will begin.

7.2.2 Path Search

A different approach would be to use a path search. Using the interface discussed in Section 7.4, different points can be selected on a map. The device will fly from one point to the next, searching for the missing individual. This technique would be particularly useful if the rescue workers have an idea of where the missing person may be. After the path is selected, the system will return a 3D plot of the flight altitude needed to stay 240m above ground, which was the flight altitude determined for the detection system

(Subsection 8.2.1). In Figure 7.7 such a flight profile for the Dolomomites is presented. The ground distances are given in kilometers from the staring point of the created map and the height is given in meters. As can be seen in Figure 7.7, the altitude differs significantly during flight in the given example. The rescue worker would be given such a plot together with a power and time estimation. The mission could then be confirmed, after which *Nora* will begin its search.

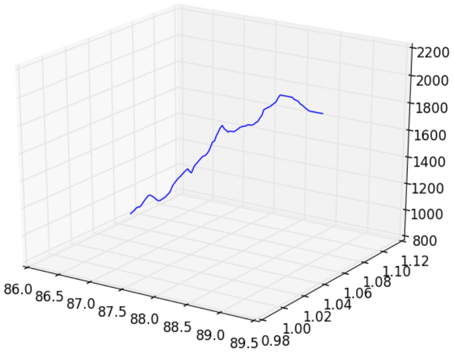
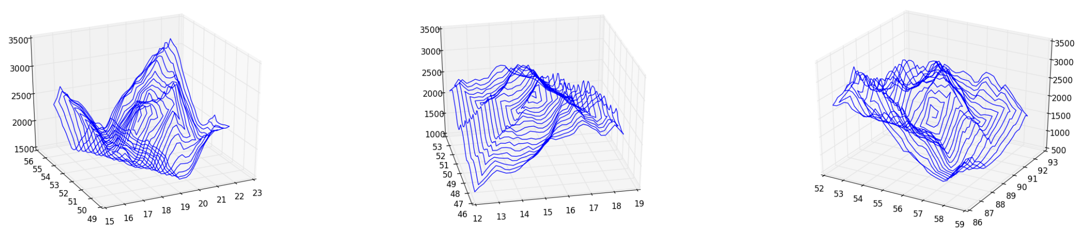


Figure 7.7: Path Search Example (X- and Y-axis in Geographical Coordinates and Z-axis in Meters)

7.2.3 Area Search

A possible search pattern would be to cover the entire area, starting from a selected point. This method would be beneficial when height differences are small within the area. The rescue worker can select the starting point after which the entire area is covered using a spiral motion. It was decided to use a square spiral motion to be able to fly in cruise mode as much as possible. Naturally the turns have to be adjusted by the minimum turn radius for the in flight application. The flight height can be determined along the entire search path, to avoid collision with a mountain within the search area. A minimum and maximum height in the area will be presented along with 3D plots of the needed flight profile if the height above ground remains a constant. It should be noted that, since the altitude is only determined per every $30m$, the plots will not fully resemble reality. The flight lines are separated by $190m$, which is the ground coverage determined in Subsection 8.2.1. In Figure 7.8a, 7.8b and 7.8c a spiral motion for a specific mountain terrain is presented. In all figures there are height differences that have to be overcome. The rescue worker can on site determine whether or not such a flight profile is desired.



(a) Spiral Flight Path 1 (b) Spiral Flight Path 2 (c) Spiral Flight Path 3

Figure 7.8: Three Spiral Flight Paths using SRTM Data [14]

7.3 Operator Procedures

Apart from the operations of *Nora* herself, the operator (i.e. user of the *Nora* system) forms another party involved in the search mission. Implementation of *Nora* in mountain rescue teams should be supplemented with detailed required actions by the operator. Such procedure may best be described by means of an operational diagram, as given by Figure 7.9. The figure shows for all distinguished mission phases (being mission initiation, takeoff, cruise to area, search flight, package delivery and landing) the necessary procedures for both the incident control as well as the search parties. The basis was set by the *Search Actions Outline*, a general planning guide for mission initiation by the incident control and extended with *Nora* related procedures. [16]

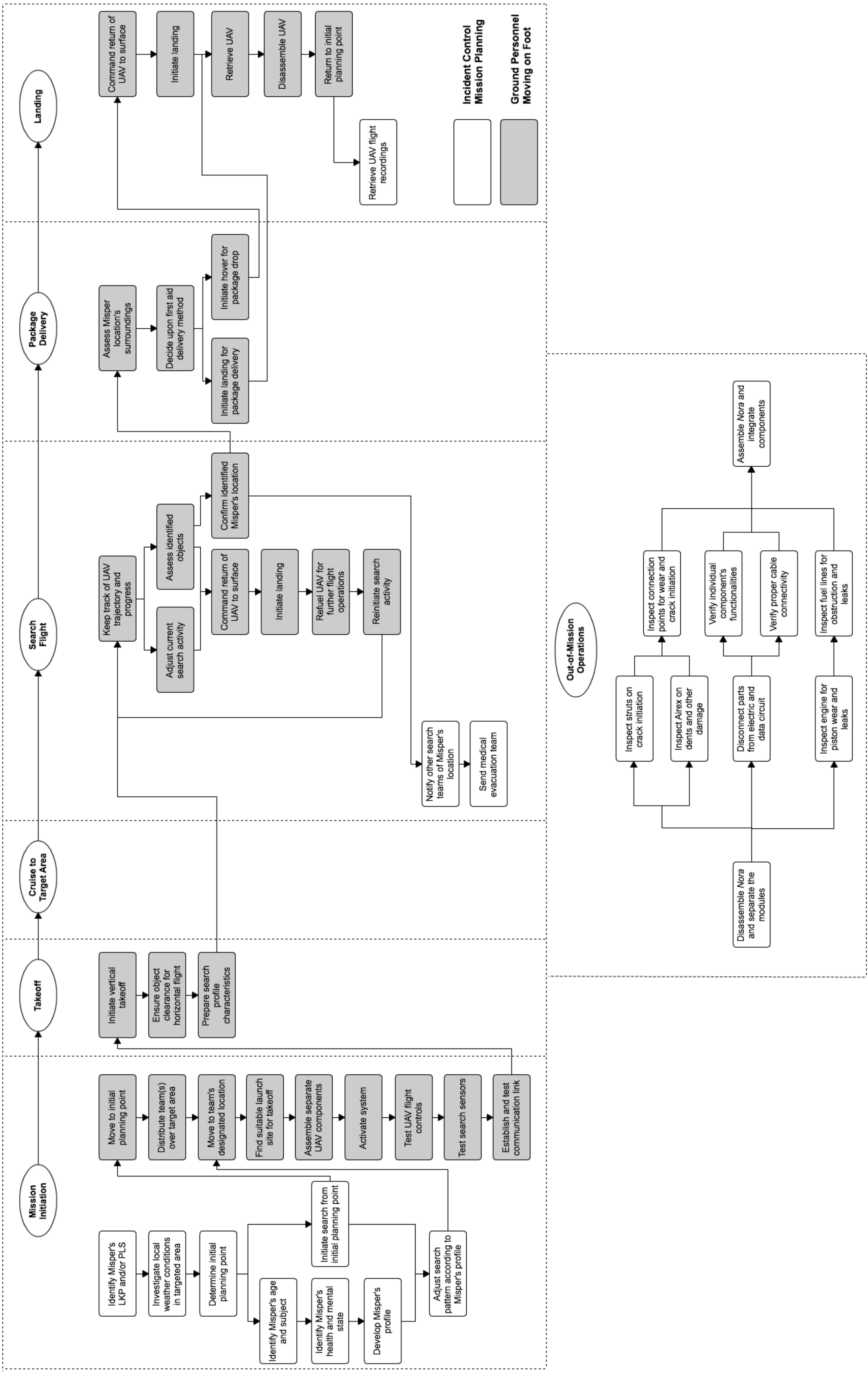
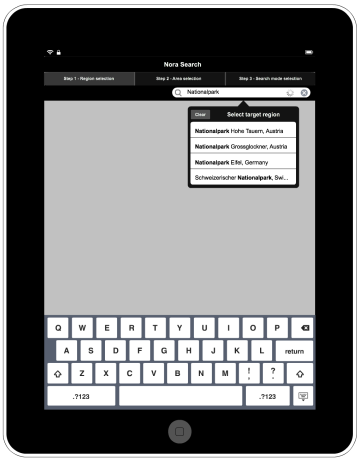


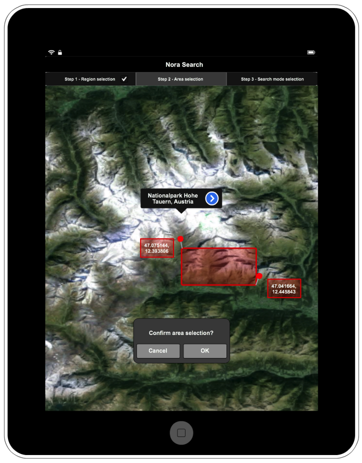
Figure 7.9: Overview of *Nora* User Procedures

7.4 Ground Station Interface

During market research it was found that every search and rescue mission is different. The *Nora* system will thus have to have the ability of handling diverse mission strategies and operation characteristics. A single, ideal search pattern does therefore not exist. It depends on the height profile of the mountains, lines of least resistance and the profile of the missing person. To accommodate for this different search patterns were developed (Section 7.2). This section gives an impression of the guided user interface to be used by the search and rescue personnel during their actions described in Section 7.3. The search pattern has to be selected at the beginning of the mission and can also be changed during operation. Figure 7.12 shows the steps to be taken when selecting the spiral search mode. In Figure 7.10a, the mountain terrain desired can be entered. This will yield a map were a specific area can be selected, as in Figure 7.10b. Just as in Figure 7.11a, a 3D view and a height map will be made of the selected area. Here the search mode has to be defined. When selecting the spiral search mode a starting point and a radius have to be entered (Figure 7.11b). When confirming the chosen parameters, a 3D view of the spiral path is given together with a time and energy consumption estimation. Furthermore the total energy still available is also displayed. When the rescue worker approves the mission, it can be confirmed. Figure 7.12b shows the search profile during flight. The passed time, the used energy and the position in the 3D images can be found at all times. Once the system has detected an individual it is up to the search and rescue team to confirm the found person has the correct identity. This is again done using the tablet interface. Figure 7.13a, shows an example of such a detection scenario. Multiple frames in which *Nora* detected the person can be made visible by swiping the image on the screen. The detection method is described in detail in Section 8.2.1. The identification can be confirmed by simply pushing the green bottom on the interface, displaying target location and planned path.

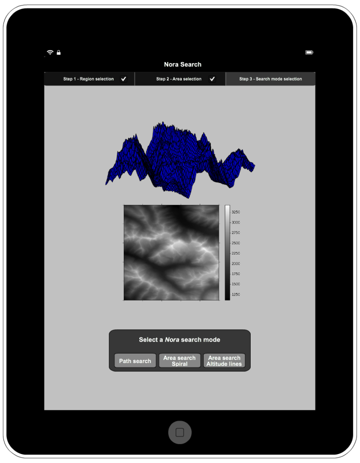


(a) Selecting the Mountain Range

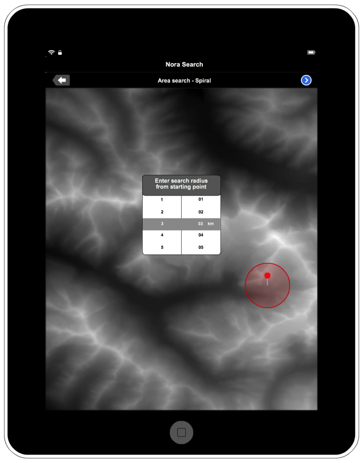


(b) Choosing the Desired Area

Figure 7.10: Interface for Selecting the Desired Area

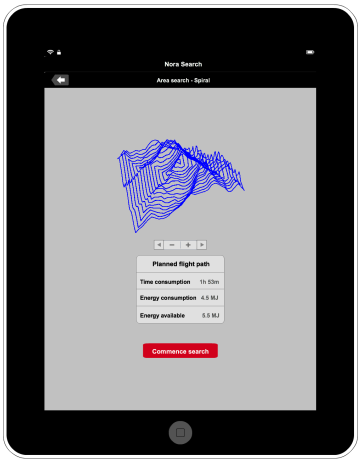


(a) Selecting *Nora* Search Mode

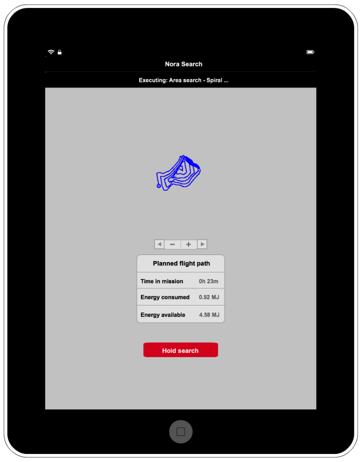


(b) Set *Nora* Search Mode Input Parameters

Figure 7.11: Interface for Selecting the Desired Search Mode

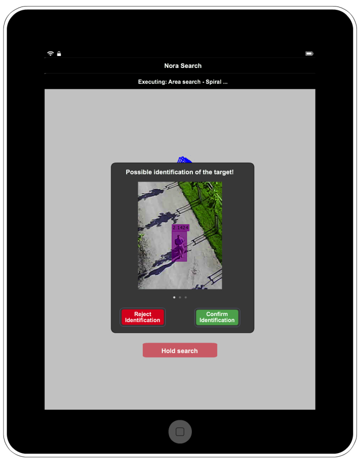


(a) Search Mode Overview and Initiation

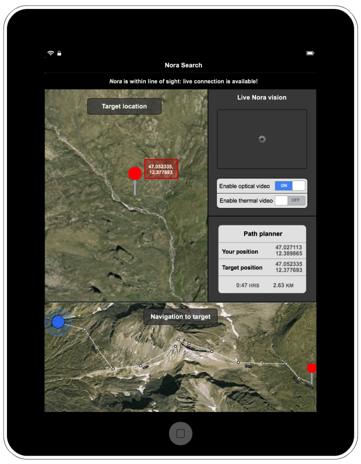


(b) Search Mode Current Progress

Figure 7.12: Interface for Checking the Progress of the Search Mode



(a) Manual Decision on Possible Target Identification



(b) Identified Target Location and Trail Planning

Figure 7.13: Interface for Identifying a Located Individual

8 | Preliminary Operational Design

Nora's main goal is to make the operational aspect of SAR missions more effective. Therefore a key part in the design of the system was the preliminary operational design, which will be discussed in this chapter. Topics discussed are the communication subystem in Section 8.1 which ensures communication between *Nora* and the operator. After that the detection system is elobarated upon in Section 8.2. The collision avoidance system is outlined in Section 8.3 to ensure safe flight. Finally the data handling of *Nora* can be found in 8.4 accompanied by software flow diagrams.

8.1 Communication

Communication is of utmost importance to achieve success in operations. To communicate efficiently during operations, a wireless system is necessary to send data to and from *Nora*. As can be seen in the subsystem requirements, a data rate of at least $7.5Mbits^{-1}$, an average power consumption of $4W$, a maximum power consumption of $10W$, a mass less than $0.5kg$ and a communication range up to $50km$ has to be achieved [3]. Two types of wireless communication are considered to accomplish these requirements: satellite communication for non-line of sight or long range and line of sight (LOS) communication for close range. Other options such as the GPRS and LTE terrestrial networks[1] are not taken into account due to the lack of available infrastructure in the operational environment.

LOS communication is largely influenced by the surroundings (e.g. trees and mountains) which makes it impossible to have LOS during the whole mission and certainly not with a $50km$ range. On the other hand, LOS communications can be designed such that data rates up to $187Mbits^{-1}$ are possible[2]. Satellite communication excels in the operational availability of the system, which is not influenced by events on ground, e.g. an earthquake that destroys infrastructure. Next to that, satellite communication is an accepted format for communication during SAR operations[3]. On the other hand, satellite communication has limited data rates up to $20kbits^{-1}$ for most portable receivers[4]. Transceivers for satellite communication are also often quite large[5].

Both LOS and satellite communication will be implemented in the communication subsystem design. First a communication satellite link and LOS system is designed for both air and ground unit and their configuration is shown, followed by recommendations on how the communication system can be improved in the future. Finally, the switch between LOS and Satellite communication during flight will be elaborated.

8.1.1 Aerial Unit

The air communication unit exists of one transceiver with antenna on top of the UAV integrated in the tail for satellite communication, one transceiver with antenna mounted on the bottom of the UAV for control, commands, and navigation data transferring between ground unit and *Nora* and two transmitters with antennas on the bottom of the UAV for image or video transferring.

Satellite Communication

There are four major satellite communication networks available: Globalstar, Inmarsat, Iridium and Thuraya. Although there may be more satellite networks available such as governmental and military satellite networks such as the COSPAS-SARSAT, the sought after satellite communication network is a widely available network with coverage up to 65° latitude. Therefore these four satellites are considered to be the best options. Based on the latitude criteria, the two best options are Inmarsat and Iridium, since the Globalstar only has good coverage at high latitudes and Thuraya only provides coverage in

[1] GPRS and LTE, URL `http://www.yachtrouter.com/index.php/support/knowledge-base/95-what-are-lte-umts-hspa-dchspa-gsm`, [cited 30 June 2015]

[2] LOS communications, URL `https://www.dji.com/product/dji-lightbridge`, [cited 19 June 2015]

[3] Satellite communication, URL `http://www.excelerate-group.com/case-studies/invaluable-is-the-verdict-of-group-commander-paul-burnham-when-asked-to-describe-the-contribution-made-by-the-bgan-mobile-satellite-terminal-taken-by-the-uk-international-search-and/`, [cited 9 June 2015]

[4] Data rates, URL `https://iridium.com/About/IridiumGlobalNetwork.aspx`, [cited 30 June 2015]

[5] Transceivers, URL `http://www.inmarsat.com/service/bgan/`, [cited 4 June 2015]

Australia, Europe and Asia[6],[7]. The Inmarsat BGAN communication network has a large coverage, from $S82°$ to $N82°$ latitude and consists of three geostationary satellites. With a latency of $800ms$, the time to send data from and to *Nora* can be minimised. The operational lifespan is expected to be up to the year 2020 with 99.9% availability of the system [8]. On the other hand, the Iridium communication network with 66 active satellites, covers the whole Earth making a data link almost always possible. Iridium has a lower available data rate only up to $10kbits^{-1}$ and a latency of less than 1 minute. Next to that, the prices for data usage is up to 100 times more expensive compared to the Inmarsat prices [9]. Based on this information, the Inmarsat, with a data rate up to $20kbits^{-1}$ is considered the best option and will be the designed satellite communication module, but in regions where Inmarsat will not provide the necessary data link, an Iridium module can be used.

Based on the information provided by one of the stakeholders, the Spanish *Guardia Civil's Search and Rescue Group* which exists of 5 units, around 150 missions are carried out per rescue unit per year[10]. Assuming these missions have a duration of approximately 2 hours and *Nora* will use satellite communication for half of the mission at the maximum data rate of $20kbit/s$, *Nora* will send around $10,800Mb$ yearly per unit using the satellite communication and therefore ends up in the category with a tariff of approximately €$0.52/Mbit$[11]. The estimated price for 1 hour of satellite communication during the mission will be €38, using these assumptions and the current tariff.

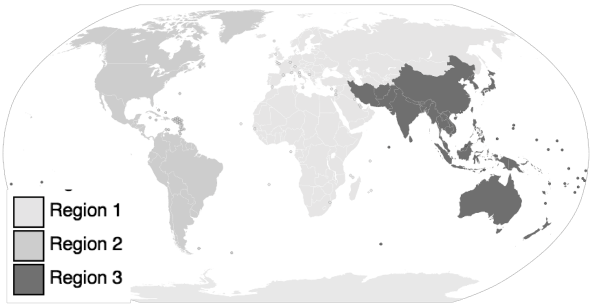
Due to the low and expensive data rate, this channel will solely be used for the control and navigation of *Nora*. Important images taken by Nora can be send to the ground unit, but it will take up to $8min$ for a 848x480 color picture, taken by the optical camera, and up to $4min$ for a 640x480 gray scale picture, taken by the thermal camera. Image compress techniques can be used to reduce the file size significantly resulting in a faster send time. Using the 848x480 color picture as an example, the send time can be reduced to $2min$ and $45s$ for a color picture with a quality loss of only 30%, generally producing an adequate qualitative picture, that can be used by the ground units. Another technique that can be used to reduce send time is image cropping of the interesting part of the picture, resulting in a smaller dimension and size, without quality loss, resulting in a send time of less than $1min$.

Line of Sight Communication
As long as the *Nora* is flying in line of sight of the rescue workers within a range of approximately $10km$, a direct link can be used for communication between the vehicle and ground unit. The relation between band, range and data rate, can be simplified as the higher the band, the higher the data rate, but the smaller the range. In order to optimize the communication for these different distances between the vehicle and ground unit, three different frequency bands are used. In order to make the system as easy as possible to use, the unlicensed international, scientific and medical (ISM) radio bands were used, as indicated in Table 8.1. These bands depend on the region where the UAV will be used. These regions are shown in Figure 8.1a [12]. Different configurations for these different regions are described in the next part of this subsection.

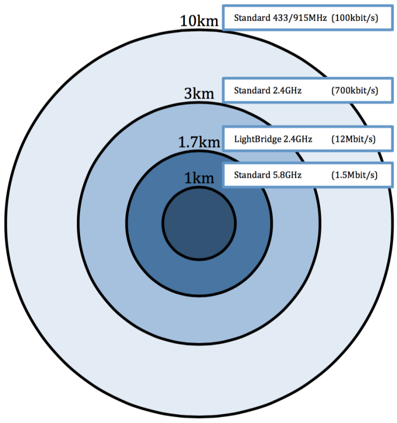
Table 8.1: International Scientific & Medical Radio Bands

Frequency Range	**Bandwidth**	**Center Frequency**	**Availability**
433.050 - 434.790 MHz	1.74 MHz	433.920 MHz	Region 1,3
902.000 - 928.000 MHz	26 MHz	915.000 MHz	Region 2
2.400 - 2.500 GHz	100 MHz	2.450 GHz	Worldwide
5.725 - 5.875 GHz	150 MHz	5.800 GHz	Worldwide

[6] Globalstar, URL `http://www.globalstar.com/en/index.php?cid=101`, [cited 5 June 2015]
[7] Thuraya, URL `http://www.thuraya.com/network-coverage`, [cited 5 June 2015]
[8] Life span, URL `http://www.inmarsat.com/about-us/our-satellites/`, [cited 19 June 2015]
[9] Inmarsat, URL `http://www.satphonestore.com/airtime/isatphonepro-airtime.html`, [cited 19 June 2015]
[10] Guardia Civil, URL `https://en.wikipedia.org/?title=Mountain_rescue`, [cited 23 June 2015]
[11] Rate, URL `http://www.groundcontrol.com/BGAN_rate_plans.htm`, [cited 23 June 2015]
[12] Regions, URL `https://en.wikipedia.org/wiki/International_Telecommunication_Union_region`[cited 22 June 2015]



(a) International Telecommunication Union Region [12]



(b) Bandwidth Range and Data Rates

Figure 8.1: Radio Frequency Figures

One could argue that these bands would easily interfere with other applications, because they are open and unlicensed, but due to the relatively low population density in mountainous environments and the possibility to switch between different channels within a certain bandwidth, a low amount of interference is expected.

The different range and data rates linked to the bands are shown in Figure 8.1b. The $433MHz$ and $915MHz$ band has an estimated data rate of $100kbs^{-1}$ up to a range of $10km$. The $2.4GHz$ band's data rate, at an estimated maximum range of $3km$, is up to $700kbs^{-1}$[13]. The third, closer range $5.8GHz$ band allows a data rate up to $1500kbs^{-1}$ to a maximum distance of $1km$ [17].

The $915MHz$ band used in the American continent or the $433MHz$ band used in the rest of the world, will mainly be used for control and navigation of *Nora*, because of the proper long range characteristics. Since information has to be both transmitted to and received from the ground unit, a $433MHz$ or a $915MHz$ transceiver with corresponding antenna will be implemented. The $2.4GHz$ and $5.8GHz$ bands will be used for the image transferring from the vehicle to ground unit. Therefore, two transmitters with antenna, one for the $2.4GHz$ and one for the $5.8GHz$ band will be implemented.

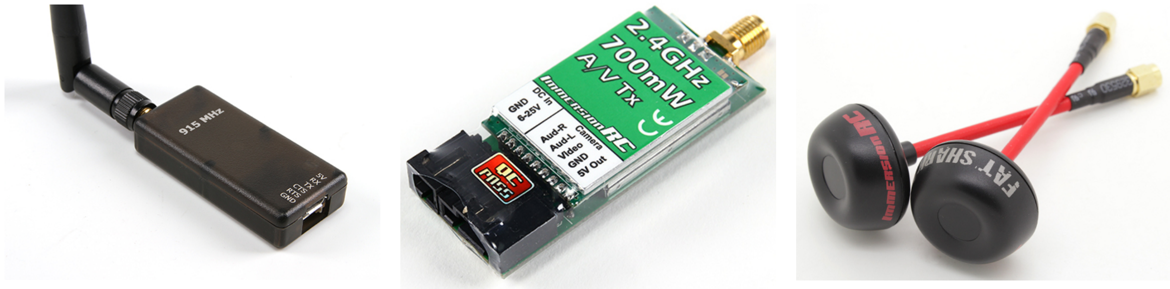
The antennas will work together to add up all the data rates in order to transfer the images as fast as possible. Software will be written to take the interference of the different antennas into account. Since the images will be sent to the ground station using different bands, the software also has to take the image data separation and compilation over the different antennas into account. For this, one has to take the difference in receive time between the frequencies into consideration.

Market analysis indicated that several stakeholders are interested in a continuously live video stream of *Nora*'s camera. The $2.4GHz$ transmitter with antenna can be replaced by the *DJI LightBridge system*, which also works on the $2.4GHz$ band and has a data rate up to $12Mbit/s$, to fulfill this stakeholder need up to $1.7km$. Due to the high cost of the ultra definition live stream, this will not be incorporated in the standard package [14].

Configuration
The final configuration is different depending on the chosen package or the region where *Nora* will be used. In Table 8.2 the components of the different options are listed. Package 1 is designed to stay within legal constraints in region 1 (includes Europe & Asia) and has an estimated weight of $140g$ for a price of €1,154. Package 2 is developed to legally use *Nora* in region 2 (includes USA) and has a weight of $150g$ for around €1,162. The live stream (LS) package is able to provide a HD live stream within a range of $1.7km$, as described in the previous section, for an extra total cost of €550 for both air and ground unit component improvements. Examples of a transmitter, transceiver and antenna can be seen in Figures

[13] 2.4GHz band, URL `http://download.dji-innovations.com/downloads/wkmwaypoint/Ground_Station_User_Manual_v2.5_en.pdf` [cited 19 June 2015]
[14] LightBridge system, URL `http://www.dji.com/product/dji-lightbridge` [cited 22 June 2015]

8.2a - 8.2c [15] [16] [17].



(a) 915MHz Transceiver (b) 2.4GHz Transmitter (c) 5.8GHz Antenna

Figure 8.2: Air Unit Components

Table 8.2: Communication Air Unit Component Budget Breakdown

Package	Part	Specification	Cost [€]	Weight [kg]	Power [W]
1, LS	433MHz Transceiver	HKPilot 500mW 433MHz Transceiver Telemetry Radio Set V2	22	0.012	0.75
1, LS	433MHz Antenna	ImmersionRC 433MHz "Sander" Antenna	1.90	0.007	0
2, LS	915MHz Transceiver	HKPilot 500mW 915MHz Transceiver Telemetry Radio Set V2	22	0.012	0.75
2, LS	915MHz Antenna	AN902RD 900 MHz 2dBi Whip Antenna	9.70	0.015	0
1,2	2.4GHz Transmitter + Antenna	ImmersionRC 700mW 2.4GHz A/V Tx	61	0.018	3
LS	2.4GHz Transceiver + Antenna	DJI LightBridge 2.4GHz Full HD V Downlink Air Unit	610	0.070	8
1,2,LS	5.8GHz Transmitter	ImmersionRC 600mW 5.8Ghz A/V Tx	43	0.018	1.5
1,2,LS	5.8GHz Antenna	ImmersionRC 5.8GHz Circular Polarized SpiroNet Antenna V2	36	0.012	0
1,2,LS	1.6GHz Transceiver	Core 9523 by Iridium satellite	740	0.032	3.1
1,2,LS	1.6GHz Antenna	Cobham SVD2-1605-HDSMA-F1/431	250	0.04	0
Region 1,3 Package Standard			1154	0.140	5.25 (LOS) 3.1 (SAT)
Region 2 Package Standard			1162	0.150	5.25 (LOS) 3.1 (SAT)
Region 1,3 Package Live HD Stream			1703	0.19	10.25 (LOS) 3.1 (SAT)
Region 2 Package Live HD Stream			1711	0.20	10.25 (LOS) 3.1 (SAT)

[15] 915MHz Transceiver, URL http://www.hobbyking.com/mobile/viewproduct.asp?idproduct=74651, [cited 30 June 2015]

[16] 2.4GHz Transmitter, URL http://www.hobbyking.com/hobbyking/store/__66875__ImmersionRC_700mW_2_4GHz_Audio_Video_Transmitter.html, [cited 30 June 2015]

[17] 5.8Ghz Antenna, URL http://www.toemen.nl/immersionrc-58ghz-circular-polarized-spironet-antenna-v2-sma-p-20687.html, [cited 30 June 2015]

8.1.2 Ground Unit

The ground communication unit exists of two transceivers with antenna for both satellite and LOS communication. These are used for control, commands, and navigation data transferring between ground unit and the vehicle and two receivers with antennas for image or video transferring.

Satellite Communication
In order to both transmit signals to and receive from *Nora* when she is not in line of sight, a transceiver working on the $1.6GHz$ frequency is used. This is the same transceiver and antenna as implemented in *Nora*.

Line Of Sight Communication
When *Nora* is in line of sight, the ground unit will transmit commands to her and receive information from her on the $915MHz$ for region 2, or $433MHz$ for region 1 or 3 as shown in Figure 8.1a. The same transceiver and antenna as implemented in *Nora* is used. For both the $2.4GHz$ and $5.8GHz$ band, the ground unit will use receivers and antennas, because these bands will not be used to transmit information from ground unit to the vehicle. When opted for the *DJI LightBridge* system, the $2.4GHz$ receiver and antenna will be replaced by the $2.4GHz$ ground system included in this package.

Configuration
The configuration of the above described systems is listed in Table 8.3. The ground unit package for region 1 will have a weight of $313g$ for the price of €1, 087. For region 2, the package will cost €1, 095 and will have a weight of $321g$. Lastly there will be an additional weight of $190g$ for the ground unit when opted for the LightBridge live stream data link. Examples of the *DJI LightBridge* ground and air transceiver and a receiver can be seen in Figures 8.3a - 8.3b [18] [19].

(a) 2.4GHz DJI LightBridge Ground/Air Components

(b) 5.8GHz Receiver

Figure 8.3: Ground Unit Components

8.1.3 Future Improvements

Future possibilities to increase the performance of *Nora* or communication system is the use of a directional helical antenna with an automatic pointing mechanism at either the vehicle, ground unit or both. The gain will increase, resulting in better communication characteristics as the data rate at further distances will increase. Another way to increase performance is to use an amplifier to increase the power. Since the maximum power is limited by regulations, a license will be needed. Another recommendation is to incorporate the antennas in the struts of the landing gear in the future, resulting in better aerodynamic performances of *Nora*.

It must be noted that a choice has been made, based on the global availability of the systems. It might

[18] DJI LightBridge, URL http://www.hobbyking.com/hobbyking/store/__54882__DJI_LightBridge_2_4GHz_Full_HD_Video_Downlink.html, [cited 30 June 2015]

[19] 5.8GHz Receiver, URL http://www.aliexpress.com/store/product/Boscam-RC805-5-8Ghz-8-Channels-8CH-Wireless-Video-Audio-AV-Receiver-Wholesale-Free-Shipping-170168/402153_1534237761.html, [cited 30 June 2015]

Table 8.3: Communication Ground Unit Component Budget Breakdown

Package	Part	Specification	Cost [€]	Weight [kg]	Power [W]
1, LS	433MHz Transceiver	HKPilot 500mW 433MHz Transceiver Telemetry Radio Set V2	22	0.012	0.750
1, LS	433MHz Antenna	ImmersionRC 433MHz "Sander" Antenna	1.90	0.007	0
2, LS	915MHz Transceiver	HKPilot 500mW 915MHz Transceiver Telemetry Radio Set V2	22	0.012	0.750
2, LS	915MHz Antenna	AN902RD 900 MHz 2dBi Whip Antenna	9.70	0.015	0
1,2	2.4GHz Receiver + Antenna	ImmersionRC Uno2400 2.4GHz FPV A/V Rx	55	0.17	3.8
LS	2.4GHz Transceiver + Antenna	DJI LightBridge 2.4GHz Full HD V Downlink Ground Unit	614	0.36	8
1,2,LS	5.8GHz Receiver + Antenna	SkyZone RC805 - 5.8Ghz 8 Channel AV Receiver	18	0.052	2.6+
1,2,LS	1.6GHz Transceiver	Core 9523 by Iridium satellite	740	0.032	3.1
1,2,LS	1.6GHz Antenna	Cobham SVD2-1605-HDSMA-F1/431	250	0.04	0
Region 1,3 Package Standard			1087	0.313	7.23 (LOS) 3.1 (SAT)
Region 2 Package Standard			1095	0.321	7.23 (LOS) 3.1 (SAT)
Region 1,3 Package Live HD Stream			1642	0.503	11.39 (LOS) 3.1 (SAT)
Region 2 Package Live HD Stream			1650	0.511	11.39 (LOS) 3.1 (SAT)

be that there are alternatives that better suit the needs of our potential customers. The communication subsystem will therefore be modular, to provide the customer with the possibility of a communication subsystem that fit their needs and/or current communication system.

8.1.4 Communication System Switch

The LOS communication is favoured over the satellite communication due to higher possible data rates and lower costs for data transmission. Therefore, it is necessary to describe the switch between these modes. When the location of both the operator and the vehicle are known, the range can be determined. Combined with the height maps used for flight lines, a model can be made for LOS communication. As can be seen in Figure 8.4, three modes are indicated. In this figure, the white curved line represents the cross section of a mountain. The three modes are satellite, LOS, or the combination of these two within the transition phase. If possible, *Nora* will always try to switch to LOS communication.

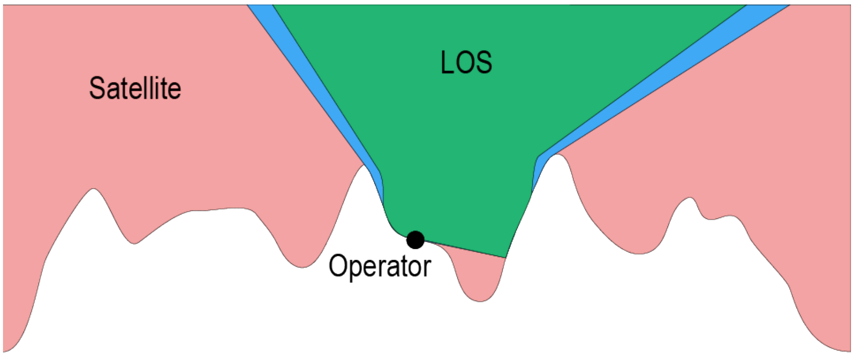


Figure 8.4: Communication Subsystem in Operation

8.2 Detection

Detection plays a key role in the design of a UAV for the SAR mission of missing individuals. In the Baseline and Midterm Phase of the project research was done into multiple different sensors that could be used for detection. As was concluded in the *Baseline* Report [2], four sensors options were considered feasible for the detection of missing persons and thus investigated more extensively; both optical and thermal imaging, acoustic sensing and radio frequency scanning. In the *Midterm Report* a basic understanding of the sensors was attained and a mission profile fitting the detection system's needs was developed [3]. In the Final phase, the research into the detection sensors was extended and a method for processing the acquired data was developed too. In Subsection 8.2.1, the study into and the decisions made on optical and thermal camera's can be found. Subsection 8.2.2 elaborates on the microphone system and the processing techniques needed to assure a working system. Finally, in Subsection 8.2.3, the radio frequency antenna system is presented.

8.2.1 Optical and Thermal Imaging

In the following section, the optical and thermal imaging process will be explained in detail. First the study on cameras in general will be clarified, after which an enumeration of possible options is brought forward. Additionally, a description of data processing methodology will be given. To conclude, eventual decisions and resulting system characteristics are presented lastly.

Research on Optical and Thermal Imaging

As was explained in the *Midterm report*, it is of paramount importance to the successful deployment of both thermal and optical camera enhanced detection systems that the features of the device are well understood [3]. A thermal camera is a device that forms an image using the infrared spectrum and works similar to an optical camera that forms an image using visible light, only it detects different wavelengths. This makes that it is able to detect thermal radiation. Essential elements regarding the possibility of detection in imaging are described by Johnson's Criteria; an important model for the determination of the preliminary features of the imaging detection system. This model defines three main types of sensing tasks, being detection, recognition and identification (DRI), as listed below. Note that the orientation search phase has been left out, since its usefulness was found to be minimal with respect to others. [18]

- **Detection:** Phase meant for notification of the operator about the presence of heat radiating objects. The imaging sensor is capable of detecting an object at a pixel range of 2.0 ± 0.5 pixels.
- **Recognition:** Recognition phase allows the operator to categorise the detected object. The imaging sensor is capable of recognising the type of object at a pixel range of 8.0 ± 1.6 pixels.
- **Identification:** Phase during which detected/recognised objects can be identified as actual target. The imaging sensor is capable of identifying the type of object at a pixel range of 12.8 ± 3.0 pixels.

The different phases described by Johnson's Criteria can be adopted to resolve the maximum altitude at which a certain search type may still be carried out. Naturally, the detection phase requires least pixels and therefore the altitude at which this phase may be carried out is highest. A visualisation on pixel requirement per search phase (and thus image detail) by Johnson is given by Figure 8.5.

(a) Detection Phase (b) Recognition Phase (c) Identification Phase

Figure 8.5: Ground Images of Different Search Phases [19]

Key information, provided by Johnson and implemented for the operations design, is the requirement on number of pixels per level of image detail. Johnson's Criteria sets a minimum range of pixels that must be caught along the critical dimension of the target. Although brochures by FLIR state a human body critical dimension may be assumed to be $0.75m$, others simply take it as the smallest dimension of the target's surface as registered by the image sensor [19]. Problems may arise when insufficient effective signal from the radiating source is caught on the imaging surface. Although phases other than detection may find similar occasions, poor results during detection phase may lead to a heat source not being detected at all. For recognition or identification phase, on the other hand, the image quality may admittedly be unsatisfactory, though possible targets may certainly be registered. The former was generally confirmed by prof.dr.ir. Lucas van Vliet (Applied Physics at Delft University of Technology). Whilst recognising the advantages of high altitude and corresponding ground area coverage, doubt was expressed on the effectiveness of the system at all times. *Nora* should thus accommodate an imaging system that is both affected by various parameters as well as affecting several characteristics such as flight altitude. Several major design driving factors have been identified and are enumerated below.

1. The imaging system shall be designed to achieve as much ground coverage as possible
2. The chance of non-detection of heat sources during detection phase shall be carefully incorporated
3. The design altitude shall be feasible with the operation of *Nora*
4. The high cost of thermal imaging shall be handled as optimally as possible

These criteria should assist during the imaging system design, for which several options have been considered. All are assessed with respect to the aforementioned factors in the following part.

Contestant Imaging System Designs

Throughout preceding design phases, numerous concepts have been thought of that were to fulfill the localisation of a (or more) missing person(s). In this part, the most advanced and varying concepts will be clarified and graded on ground coverage, system cost, altitude and probability of detection.

1. WFOV Detection & NFOV Identification Cameras

Initial concepts, firstly described in detail in the *Midterm Report*, comprised two identical thermal cameras where one would be supplemented with a Wide Field of View (WFOV) lens for detection, whilst the other would perform identification with a Narrow Field of View (NFOV) lens. Although a single lens could have performed such mission profile, too, it would have to be brought to much lower altitude for identification and up again for more ground coverage. This design thus scores well on design altitude and ground coverage, the need for two cameras leads to a more costly design and flight on maximum detection altitude could possibly lead to the need for alterations during prototype testing. The latter was the main point made by prof.dr.ir. Lucas van Vliet and as a result, other system configurations were proposed.

2. Super Resolution Frame Merging System

Images shot from several cameras could be combined using the technique of Super-Resolution as proposed in multiple theses [20] [21]. In Figure 8.6 a flow diagram of this technique is presented. Due to the forward velocity of the vehicle, multiple yet slightly differently orientated images are shot of the area. First, all the images can be combined into one image to enhance image quality. This image will already have a better resolution due to image registration at either identification or recognition altitude, though could be further improved using advanced filter techniques such as separable bilateral detection. This method

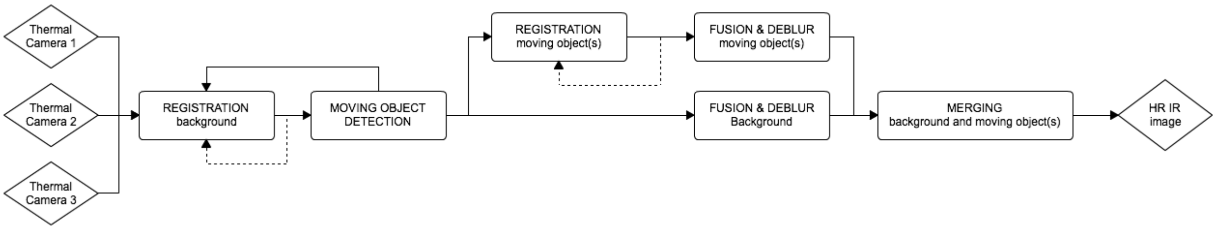


Figure 8.6: Super-Resolution Software

has proven to work very well when the camera is moving and common techniques can be used. However, this approach requires a lot of processing power and in most applications is not done in real time. In order to move on to the data processing phase as described in the eventual system and software configuration, a sharp image has to be available during flight at all times. It was found, supported by prof.dr.ir. Lucas van Vliet, that real time processing techniques for this application have been implemented, but only in classified applications. This leads to, although scoring high due to lower probability of non-detection, an average grade on design altitude and low scores on ground coverage and cost due to several cameras on board and the need for advanced software.

3. Dual Titled Recognition/Identification Camera System

One could also design *Nora* to fly at either recognition or identification height without Super-Resolution. The detection system would become much simpler; the identification camera would not have to constantly point at the detection spots. This means that less problems will arise when considering the speed of *Nora*, since the time it takes to point the camera at the detection spot will not have to be considered. However, the system is far from flawless; first of all the design altitude is lower than previous options and so is the ground coverage achieved. The latter could partially be overcome by adding a second, identical system to double ground coverage, though increasing costs is inevitable there. The design would thus score above average on non-detection probability, but design altitude and either ground coverage or system costs would leave the design undesirable, given the number of cameras chosen.

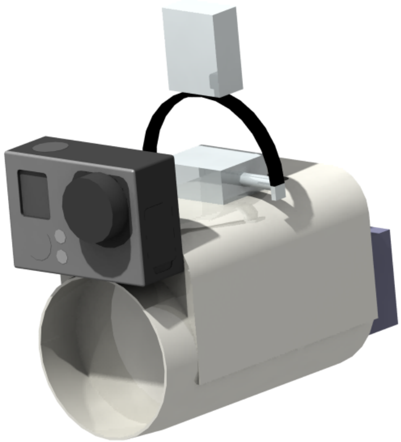
4. Motorised Zoom Lens Thermal Image System

The last variant is to some extent a spin-off from the first design, yet offers two major improvements. The system would take the form of a single thermal camera with special zoom lens, which enhancing features may be included directly into system regulating circuits. Although lenses may easily cost several hundreds up to thousands of euros, thermal cameras are usually indicating the final costs. For this very reason, having a single camera with variable lens distance seems a major improvement over the first option. Moreover, the variable lens means the field of view (FOV) and flight altitude may be optimised for every operation separately, which would prove very useful to the need for improvisation as was found during the market analysis. The design would moreover score high marks for ground coverage, design altitude and system costs, whilst have a lower score due to the chance of non-detection.

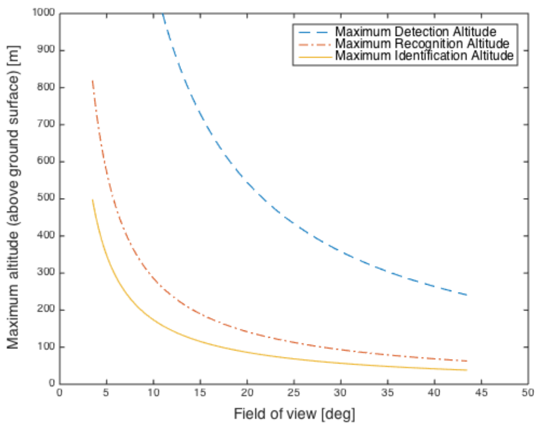
The eventual system was selected following a compromising procedure. Benefits and drawbacks of each and every design were thoroughly considered, especially on sensitivity with respect to remaining components of *Nora*. As such, the last option was held most desirable for several reasons. First and foremost, it provided *Nora* with the highest ground coverage that could theoretically be achieved. Although the probability of non-detection remains detrimental, the system may easily be adopted to new altitudes and different fields of view to raise the chance of detection. Having said that, no guarantee can be given at all for detection of any object by optics, both in normal and IR spectrum. It was therefore deemed wise to design for a (perhaps) slightly lower detection chance, but much higher ground coverage; being limited to low area coverage directly feeds back to theoretically no chance of detection in areas not being searched. Ultimately, the thought of high mobility and elevation of aerial vehicles is what makes them desirable means of search platforms. Moreover, the configuration only accommodates one camera and thus has better cost characteristics. Lastly, the lens allows for easy chance in mission profile; it is much less restricted by flight altitude and fixed fields of view. All together, the system was thought to be an optimal variation of several characteristics of the preceding designs and thus taken as final imaging detection design.

Preliminary Image Detection System

The design will thus, as stated above, include a single thermal imaging module placed after a motorised zoom lens. Its capabilities may be computed according to Johnson's Criteria, introduced earlier in this subsection. Moreover, the optical camera and corresponding lens characteristics may be determined likewise. These components will be fixed, along with the thermal camera and lens, to the image pointing system. Figure 8.7a shows the layout. Although the thermal camera may easily track heat radiating objects, optical imagery was added for easier manual identification by mountain rescue teams. It would therefore have to be capable of identifying (using Johnson's Criteria on required pixels along the critical dimension) at the same altitude as the thermal camera to remain at maximum ground coverage characteristics.



(a) Imaging Detection System Layout



(b) Maximum Altitude for Various Search Phases

Figure 8.7: Imaging Detection System Layout & Characteristics

Exact computation of altitude and corresponding ground coverage is performed by combining the above data with previously defined pixel ranges by Johnson's Criteria, the maximum altitude may firstly be computed. The ground image dimensions and surface coverage per hour can then easily be determined (given the flight speed is a known parameter), leading to a procedure as follows:

1. Establish the required amount of pixels required for a certain search phase. This step-by-step plan will continue with 2.5 pixels required for detection, though the methodology remains the same. This parameter defines the number of pixels required along the critical dimension of the to be detected object. The maximum width and height of the ground image then simply follow from the required amount of pixels per meter and the available pixels from the thermal sensor.
2. The maximum altitude, at which the attained ground image dimensions do not exceed the previously determined maximum ground image dimensions, may be deduced from the tangent of altitude and ground image width or height, whichever is smallest and thus limiting in operational altitude.
3. The last step is dependent on three parameters: flight altitude, ground speed and field of view. Note that flight altitude was found using the maximum allowable ground image dimensions. One could thus claim that the coverage can be described as the product of ground speed and maximum ground image width. Undoubtedly the latter is true, though one may prefer to fly at a predefined altitude. As a result, the new ground image dimensions will have to be computed in reverse from previous step and thus not necessarily take the maximum, but any altitude as input. Once these dimensions have been computed, the instantaneous ground coverage of one image may be found as the product of image field width by height. During flight however, the coverage may be taken as the product of ground image dimension across field track of *Nora* and its speed, given in square kilometers per hour. Naturally, this is highest when flying at maximum altitude, since the field of view is optimally used in such situation.

The aforementioned procedure has been applied to the chosen design components, with Figure 8.7b as result. The field of view in the figure ranges from 3.6° up to 43.4° in accordance with the largest field of view obtainable with the Fujifilm motorised zoom lens. At this point in the design stage, the operation was chosen to be at a constant altitude of about 240m above the surface with the following reasoning:

241.2m is the lowest maximum altitude for detection search phase. As such, the ground coverage achieved remains at a maximum whilst the distance between imaging sensor and to be detected object is kept as small as possible. Moreover, should the combination of used lens distance (and so field of view) and operational altitude provide results that are of insufficient quality to detect or identify a target, a larger margin of lens distance (and thus effectively more zoom) remains available. Additionally to the infrared images taken by the thermal camera, optical images will be sent to ground personnel for identification with more ease. The optical camera should be able to comply with Johnson's Criteria at identification phase, just like the thermal camera. GoPro is famous for its high quality and low weight cameras. For *Nora*, their GoPro Hero3 model has sufficient pixels both across as well as along track, if a modified lens is used [20]. The original lens will thus have to be replaced by a 25mm lens by Peau Productions, supplemented with SuperMount [21]. The modified optical camera will be placed in parallel to the thermal camera and provide the operator with as much visual information as possible. To store all this information on the highest resolution possible, the largest possible micro SD card is used, with a capacity of 64GB[22].

The zooming in on a detected object compels the need for a mechanism that points the field of view towards the detected object once zoomed in. Unless the target is directly below the detection system, the reduction of ground image dimensions would mean the object is no longer visible. As can be seen in Figure 8.7b, the field of view across ground track has to lessen from 43.4° to 7.2°, reducing the ground image width from 192m to 30.4m. Note that the field of view for identification of 7.2° is not the highest zoom that can be gotten out of the lens, and so some surplus remains if additional zoom is needed. In order to be able to zoom in on all spots which are initially visible, a camera pointing system is needed. Also during normal flight, when the aircraft is rotating and shaking due to gusts, the camera needs to be able to correct for this. The camera pointing system can be seen in Figure 8.7a, where the two white block objects on top indicate the positions of the two different servos used. One servo controls the left and right (yaw) movement of the camera while the other servo is controlling the up and down (pitch) movement of the camera. The required change in angle for zooming is about 20° in both directions but during maneuvering the required change in angle can be up to 70° due to roll of the vehicle. The speed of change in angle has to be fast enough such that different spots can be analysed for identification in short time while still flying fast. This requires the servos to be fast and powerful. The precision of the camera pointing is crucial as this enhances the quality of the image and the locating of the person. Therefore the 'DS8231 Ultra Precision Servo' is chosen to be most suitable for the camera pointing system as it is lightweight (20g), fast (0.19s per 60°) and precise (0.02°). This enables the camera to zoom in on different spots when necessary and together with previously defined parts, they form the major set of components for the imaging detection system. These are, with their cost, mass and power, given in Table 8.4. Moreover, the table states the image processing element and its storage, required for enabling computer vision.

During detection and identification search phase, a software program will be monitoring data at all times. For detected objects, a relative simple program is written that registers heat source on the thermal sensor, relating detected object to its location. The angle required across track may be computed, knowing the deviation of the across track location from the image center. The angle that must be kept to keep the object within zoomed in vision along track changes constantly due to the velocity along track. However, since parameters like aircraft attitude and velocity are known to the system, the program would not require any extraordinary modules or complex computations. Registration of heat sources and proper identification is, on the other hand, only possible with more advanced software. MathWorks has multiple ways of implementing computer vision and provides many examples [23]. An important thing to realise is that many of such applications concern motion tracking from a stationary point of observation. *Nora* will have to perform similar tasks in motion, for which two methods by MathWorks were considered feasible:

- **Face Detection:** Making use of predefined cascade objects such as faces, upper bodies or even pairs of eyes, this method recognises shapes within a video file. It is a relative fast, real-time

[20] GoPro Hero3, URL http://shop.gopro.com/EMEA/cameras/hero/CHDHA-301-master.html, [cited 30 June 2015]
[21] GoPro Lens, URL http://peauproductions.com/store/index.php?main_page=product_info&cPath=137_139_157_142&products_id=789, [cited 30 June 2015]
[22] 64GB Micro SD, URL http://www.dataio.nl/product/64gb-micro-sd-extreme-pro-sandisk-u3-95mbs-actie/?gclid=CKizu8eNrcYCFSgGwwodi10OSg, [cited 26 June 2015]
[23] MathWorks Toolbox, URL http://nl.mathworks.com/products/computer-vision/, [cited 30 June 2015]

Table 8.4: Thermal & Optical Detection Cost Mass & Power Budget

Part	**Specification**	**Price [€]**	**Mass [kg]**	**Power [W]**
Optical Camera	GoPro Hero3 White	210	0.069	4.5
Optical Lens & mount	Peau Productions custom 25mm for GoPro Hero3	120	0.04	-
Optical Camera Storage	SanDisk Extreme PRO micro SDXC UHS-I Card 64GB	59.00	0.001	-
Thermal Camera	BAE Systems TWV640	6100	0.04	1
Thermal Zoom Lens	Fujifilm 12x Motorised Zoom Lens (6-72mm)	510	0.33	<1
Pointing System	Self made	1	0.05	-
Servo (2x)	DS8231 Ultra Precision Servo	160	0.04	$1 - 10W$
Image PE	The Parallella Board by Parallella	200	0.038	5
Image PE Storage	SanDisk Extreme PRO microSDXC UHS-I Card 128GB	59	0.001	-
Total		**7419**	**0.609**	**11.5**

processing method, but is strictly kept to the selected cascade object. The method is therefore said to be fast, but more sensitive than *People Detection* [24].

- **People Detection:** The second method uses trained objects, too. It may, however, be adjusted with certain parameters to change the level of certainty that must be acquired by the system to give a signal of recognition. Simulation of examples provided by MathWorks brought forward that the method is more processing intensive than face detection, whilst it did prove to be more robust.

(a) Face detection

(b) People detection

Figure 8.8: Types of MathWorks Computer Vision (from Aerial Perspective)

Both methods are shown in Figure 8.8 and have been found to function on video files provided by personal drone recordings. Neither of them were optimised for aerial searching, as the cascade or reference data consisted of footage from ground situations. Since the training of cascade objects and reference data is a complex and time consuming process, the software has only been proven to work with available data.

Although aforementioned procedures indicate computer vision surely is possible and may be implemented in *Nora*'s design, the exact appearance will not host MathWorks related toolboxes for the following reason: its core program and modules are quick development tools and not supported by production tool elements such as the Parallella Board[25]. The construction of *Nora* computer vision software will therefore be done within OpenCV, such that the relative cheap processing element by Parallella may be

[24] MathWorks Face Detection, URL `http://nl.mathworks.com/help/vision/ref/vision.cascadeobjectdetector-class.html`, [cited 30 June 2015]
[25] Parallella Board, URL `http://www.parallella.org/`, [cited 26 June 2015]

used. It accommodates an integrated Field-Programmable Gate Array (FPGA) along with a multiple core processor. The overall implementation of the software is easily attained due to the possibility to connect the FPGA directly onto the General Purpose Input Output (GPIO). Such choice characterises the embedded system of *Nora*; selection of software and hardware elements is made by thought-through matching of required software capabilities and according components. It was found, for instance, that multiple core processors are exceptionally useful for image processing. The software could then be stored on separate storage devices, along with registered data during the mission. Since the Parallella board works with a large amount of data, the same micro SD storage is used as the one for the GoPro Hero3.

8.2.2 Acoustic Sensors

In the process of detecting missing individuals acoustic sensors were proposed as a potential solution in the *Midterm Report* [3]. The sensors would be used to detect people screaming for help. To ensure the lost person starts yelling, *Nora* itself would emit sound before starting a measurement. In order to implement such a sound sensor system in the designed aerial devic, several obstacles, such as a limited propagation of sound through atmosphere and the noisy aircraft environment, have to be dealt with.

Experts' opinion on aeroacoustics within the faculty of Aerospace Engineering at TU Delft was asked, in order to gain the needed knowledge, on the sound produced by the propulsion system and the wind gusts and the available methods to filter this from the measured signal, to in the end detect a yelling person. Simple equations for the propagation of sound and basic filtering methods were already considered, but verifying the proposed methods in the Midterm Report was found to be complicated [3]. From these specialists, it was found that using acoustic sensors for detection of human voices, among other things, using a small UAV is considered to be possible, but is not yet available. It was found that currently a lot of research is done on using sound sensors in small UAVs, but it has proven to be extremely difficult to filter the noise of the system. When applicable, these acoustic sensors would be used for all sorts of application and would definitely be useful in SAR application.

First the amount of sound produced on average by a person had to be quantified. The female speech spectrum reaches from $900Hz$ up to over $3000Hz$ and the male speech spectrum ranges from $300Hz$ to $750Hz$ [26]. Furthermore a human being can produce up to $88dB$ of sound, whilst yelling, measured at a distance of $0.3m$ from the source [27]. In further research, it also proved difficult to distinguish all possible missing individuals yelling. Therefore it was decided to focus solely on detecting whistle sound. These whistles enable the user to generate a very loud and clear narrow-band sound (usually a single frequency between $2 - 5KHz$), which can be perceived distinctly from long ranges and in noisy environments, without tiring the signaller. Many national parks advice hikers to carry a whistle when going into the mountains [28]. When the aeroaccoustic technology is further developed, it can always be decided to adjust the recognition software to be able to detect human voices.

During the *International Conference on Intelligent Robots and Systems* in 2012 [22] a method was proposed to detect whistle sound, whilst flying a small UAV. The primary goal of the proposed method was to detect humans in search and rescue missions and the mission proved to be able to work. However a flying wing was used in this experiment and the engine was reduced or turned off during measurement. Due to the layout of the design, it is not possible to turn off all engines and propellers and will therefore be more complicated to model. Still this solution is the best solution which is available thus far.

First a method to be able to reduce system noise had to be developed. Multiple methods will be implemented to increase the likelihood of success. Passive and active methods can be distinguished. Passive methods include those that can reduce noise before measurement and the active methods are there make the existing signal better.

- **Passive:**
  - The use of a windscreen to attenuate wind noise. By using a windscreen less noise of the propeller will be present in the signal making it easier to distinguish the wanted signal.

[26]Speech Spectrum, URL `http://www.proav.de/index.html?http&&&www.proav.de/audio/speech-level.html`, [cited 4 July 2015]

[27]Person Yelling, URL `http://www.engineeringtoolbox.com/voice-level-d_938.html`, [cited 27 May 2015]

[28]National Park Advice, URL `http://www.mountain.rescue.org.uk/mountain-advice`, [cited 14 June]

- The use of a muffler to reduce engine noise. Again less noise will be present, making it easier to find the yelling individual in acoustic signal

- **Active:**
  - Adaptive noise cancellation, which is an effective technique for removal of unwanted environmental noise

For the Adaptive noise cancellation, it is of key importance that the sound to be removed from the signal is well understood. For the propellers the sound emitted will depend on many different parameters, such as rotor speed and altitude. In reference thesis *'Adaptive Noise Reduction Techniques for Airborne Acoustic Sensors'* [23], tests were performed with one electric- and one gasoline engine powered conventional radio controlled aircraft with propeller, to determine the effectiveness of the adaptive noise cancellation techniques. The results of the experiment demonstrated that adaptive algorithms were effective at reducing unwanted aircraft noise and enhancing desired signals. In order to minimize the flow noise, which is particularly hard to model, it was decided that *Nora* will hover during measurement. In order to perform this technique an "acoustic fingerprint" will be made after producing *Nora*. For different rotor speeds the produced sound will be measured, during hover mode to filter the noise at much as possible.

The method for whistle detection will consists of three parts, after the adaptive noise cancellation is performed. First of all a method inspired on animal hearing known as Time Difference of Arrival (TDOA) is used for localizing sound sources. The classical approach to estimating TDOA is to compute the cross correlation between signals arriving at two base stations. In this way the similarity of two series as a function of the lag one relative to the other can be computed. The formula for cross-correlation between two measuring points is given in Equation 8.1.

$$R_{ij} = \sum_{n=0}^{N-1} p_i[n]p_j[n-\tau] \tag{8.1}$$

In this equation $p_i[n]$ is the signal that is received by microphone i and $p_i[n]$ the signal received by microphone j. τ is the correlation lag given by the distance between the microphones divided by the speed of sound. The maximum of the cross-correlation curve indicates where the two received signals are aligned best. The cross-correlation function is also used to determine at which base station the signal arrives first. The information yields a hyperbolic localization curve. This can be produced using Matlab software [29]. In order to achieve a 3D sound localisation, a minimum of four sound sensors have to be used. These can not be placed in the same plane for it to work. In order to reduce the processing power needed four acoustic sensors will be placed on the bottom of the fuselage. After the TDOA, the Doppler Speed Estimation is used to measure the relative speed between the target and the UAV itself. Just as for the TDOA, readily available Matlab code can be adjusted for this purpose [30]. Lastly a particle filter tracker is used which uses the obtained information, to estimate and track the position of the target. In this system false estimates are eliminated simultaneously.

As was previously explained, four sound sensors will be used in this detection system. As a microphone the FGo pro Accessories Hero Camera Stereo Microphone 10pin USB will be used[31]. These microphones cost (€4.80), weigh $0.029kg$ a piece and can easily be modular due to the USB connection. The four microphones will be spaced $5cm$ apart, in a three-dimensional plane using small sticks. This is done because of the vehicle is separable and placing the microphones on different parts makes the system a lot more complex as they have to communicate together. The system can be taken off the vehicle, when not needed in the rescue mission. The microphones will be connected to the main USB hub controller described in Section 8.4. They will however only be available as extension package, once the system has been proven to work in the *Nora* application.

[29] Mathworks 1, URL `http://www.mathworks.com/examples/lte-system/2895-time-difference-of-arrival-positioning-using-prs`, [cited 14 June 2015]
[30] Mathworks 2, URL `http://nl.mathworks.com/help/phased/examples/doppler-estimation.html`, [cited 14 June 2015]
[31] GoPro, URL `http://www.aliexpress.com/item/Go-pro-Accessories-Hero-Camera-Stereo-Microphone-10pin-USB-Professional-Microphone-For-Gopro-Hero3-hero-3/32367820177.html`, [cited 14 June 2015]

8.2.3 Radio Frequency Detection

Missing people carrying a mobile device that transmits radio frequency signals, or a radio frequency reflector, can be detected with the radio frequency antenna detection system. Generally speaking, the longer the antenna, the higher the possibility to detect lower frequency bands [32]. The same transceiver and antenna as the one used for communication on the $433 MHz$ band (or $915 MHz$ depending on the region), described in Section 8.1, will be used for detection, because this is the longest antenna mounted on *Nora* and can therefore pick up and recognize the lowest frequency bands.

The 3rd Generation Partnership Project (3GPP), a collaboration between groups of telecommunications associations, defined the 14 frequency bands, internationally used by the telecommunication operators. These bands range from $380 MHz$ (T-GSM-380-System) to $1900 MHz$ (PCS-1900-System) [33]. The RECCO reflector [34], often implemented in mountaineer‘s clothes or avalanche beacons [35] carried by them, can also be detected using this radio frequency antenna. The frequency band of these telecommunication operators, of the RECCO system and the avalanche transceiver are given in Table 8.5.

Table 8.5: Radio Frequency Bands

System Name	Band [MHz]	Uplink [MHz]	Downlink [MHz]
T-GSM-380	380	380.2 – 389.8	390.2 – 399.8
T-GSM-410	410	410.2 – 419.8	420.2 – 429.8
GSM-450	450	450.6 – 457.6	460.6 – 467.6
GSM-480	480	479.0 – 486.0	489.0 – 496.0
GSM-710	710	698.2 – 716.2	728.2 – 746.2
GSM-750	750	777.2 – 792.2	747.2 – 762.2
T-GSM-810	810	806.2 – 821.2	851.2 – 866.2
GSM-850	850	824.2 – 849.2	869.2 – 893.8
P-GSM-900	900	890.0 – 915.0	935.0 – 960.0
E-GSM-900	900	880.0 – 915.0	925.0 – 960.0
R-GSM-900	900	876.0 – 915.0	921.0 – 960.0
T-GSM-900	900	870.4 – 876.0	915.4 – 921.0
DCS-1800	1800	1710.2 – 1784.8	1805.2 – 1879.8
PCS-1900	1900	1850.2 – 1909.8	1930.2 – 1989.8
Avalanche Beacon	0.457	0.457	0.457
RECCO detection	917	917	1834

The $433 MHz$ or $915 MHz$ *HKPilot 500mW Transceiver*, depending on the location, with corresponding antenna, used for communication, will also be used to detect signals transmitted from mobile devices and avalanche transceivers, or to detect reflected signals from RECCO systems. The antenna and transceiver will detect the signals from $380 MHz$ to $1900 MHz$. Software has to be written in the the next project phase to detect signals and distinguish it from environmental noise. To determine the location of these electronic devices, calculations are done using the location of the flying UAV and the increase/decrease in received signal strength when moving in a certain direction. A range of interesting areas, where radio frequency signals are detected, can be determined and investigated. When a signal is detected, a collaboration with the other detection mechanisms on board of the *Nora* has to be performed.

The range of the radio frequency detection method is dependent on different factors and is hard to accurately determine. Tests have to be performed during the next phase of the project to find the exact operation and range of this subsystem. The frequency band is an important factor that affects the range of the detection system. Low frequency radio waves are better suitable in mountainous environment, because they diffract over obstacles and follow the curvature of the Earth due to their long wavelength. Radio frequency range is also strongly dependent of environmental effects. Rain fade is the so-called absorption of radio frequency signals by rain, snow or ice. These losses become prevalent at frequencies above $11 GHz$. The gain of the antenna can be increased, by enlarging the antenna, to take this loss effect

[32] EM Spectrum, URL `http://www.animations.physics.unsw.edu.au//jw/EMspectrum.html`, [cited 23 June 2015]
[33] 3GPP, URL `http://www.3gpp.org/about-3gpp`, [cited 30 June 2015]
[34] RECCO, URL `http://www.avalanche.org/moonstone/TAR/avi%20review%20articles/RECCO%20on%20the%20Highway.htm`, [cited 30 June 2015]
[35] Avalanche Beacon, URL `http://beaconreviews.com/transceivers/frequency.asp`, [cited 30 June 2015]

into account. Since *Nora* operates at lower frequencies, this effect would be negligible and will therefore not be taken into account.

8.3 Collision Avoidance

In combination with altitude line search discussed in Subsection 7.2.1, the collision avoidance system should ensure the flight path of *Nora* is clear. The UAV should in normal circumstances already be clear of mountain surfaces. However, since mountains do not form the only threat of collision and such event would lead to catastrophic failure of *Nora*, additional steps will be taken towards a system that can autonomously determine a clear flight path. This section will therefore briefly address the concept of optical flow and how it may be implemented into *Nora*.

8.3.1 Generalities of Optical Flow

Although optical flow may not be a common and well-known term to some, the concept can easily be understood. Even us humans make use of it to navigate ourselves. Optical flow is defined as the apparent motion of an object with respect to the observer and thus allows the observer to determine clear paths. An example is given in Figure 8.9, showing the relative motion of certain points of the image as seen from an elevated position. Not only do living beings like men, birds or insects have some sort of optical flow navigation, also robotics and other forms of unmanned devices have been shown to function effectively with optical flow . Even UAVs have been fully controlled based on vision only, providing a very robust method of navigation when compared to e.g. GPS.

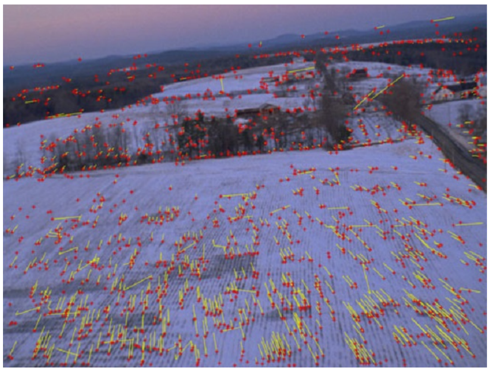


Figure 8.9: Sparse Optical Flow Example

8.3.2 Optical Flow for *Nora* Operations

Implementation of optical flow into *Nora* would be easily attained, as long as the proper equipment is considered. Off-the-shell products, that are available at prices starting from only €100, may be considered as feasible options. They are provided with a processor and all components necessary for optical flow, but may lack the accuracy or distance at which *Nora* should be able to perform this method. A more delicate system, consisting of more advanced hardware and software, would then have to be designed separately. Although the basic principle of optical flow may easily be understood and programmed in software like Matlab, situations get complex when the camera recordings its surroundings is in motion, too. In conclusion, the methodology of optical flow has been proven to work on UAVs, but its complexity in software led to the need for more in-depth research in later stages of the design process. Future analysis should point out the applicability of market available product and should these not suffice, the collision avoidance system would have to be designed by the team of *Nora* with proprietary coding.

8.3.3 Vehicle Illumination Configuration

Other than seeing from her own perspective, *Nora* should be clearly visible from any direction. This does not just hold from a safety's point of view, the Federal Aviation Administration (FAA) upholds strict rules to which any airborne system should hold. One such system is aircraft navigation lighting. The *Nora*'s lighting configuration may be found in Figure 8.10. The regulations of the FAA have been followed for the design of the lighting system, although the luminosity has been scaled down to decrease size and mass of the lights. The figure shows the positioning of various types of illumination, firstly being the navigation lights found at the wing's tips on starboard side and port side. The continuous aft light completes the navigation lighting. Additionally, *Nora* is to accommodate anti-collision or strobe lights for enhanced visibility. Lastly, lights pointed towards the rotors should illuminate rapidly rotating parts to avoid serious injures caused to the operator's limbs during operations with low visibility by darkness.

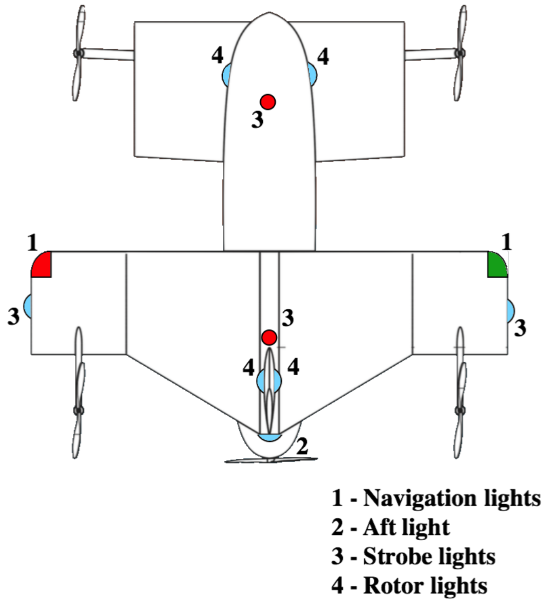


Figure 8.10: Nora Lighting System

8.3.4 Vehicle Sound System

To ensure awareness of the surroundings, a sound emitting system will be included next to the lighting system. Important is the availability of the direct current (DC) throughout the whole aircraft, therefore a DC sound emitter is chosen. To avoid complexity, a single frequency buzzer will do the trick, since this dramatically decreases cost and weight compared to full range speakers. A loud DC buzzer of 97dB will be implemented, which can be detected easily when flying over the person.

Table 8.6: Vehicle Sound System Component Budget Breakdown

Part	Specification	Price [€]	Mass [kg]	Power [W]
Navigation Lights (3x)	BL-1HL6W	49	0.03	18
Collision Avoidance Lights (4x)	BL-NavSLED	19	0.04	4
Rotor Safety and Landing Lights (2x)	BL-3HL1W	49	0.06	22
Sound Emitter	Kingstate 5V Surface Mount Electromagnetic Buzzer, 97dB	1.50	0.0007	0.4
Total		**118.50**	**0.13**	**44.4**

8.4 Data Handling

To obtain integration of all subsystems, a hardware diagram, software diagram and communication flow diagram were made. As can be seen in Figure 8.12, the communication flow diagram of *Nora* is shown. The main internal communication system consists of a USB 3.1 type-C system [24]. This choice is mainly based on the reversibility of the port, the high data rate capability, the possibility for power distribution up to $100W$ and the backward compatibility. Finally, the bus system is widely used in computer systems. Making it a versatile and therefore excellent connector in terms of modularity. All the indicated Processing Elements (PEs or Processors in the diagram) consist of a processor and on board memory modules as described by the product specification. Data rates or data clock speeds are indicated. For the detection subsystem, it is necessary to mention that the 4-port USB Hub Controller will make place for a custom interface board to improve latency and achieve better real-time processing performance. The interface board will convert CameraLink and HDMI from the thermal imaging sensor and the optical imaging sensor to GPIO that goes directly in the FPGA of the Parallella board.

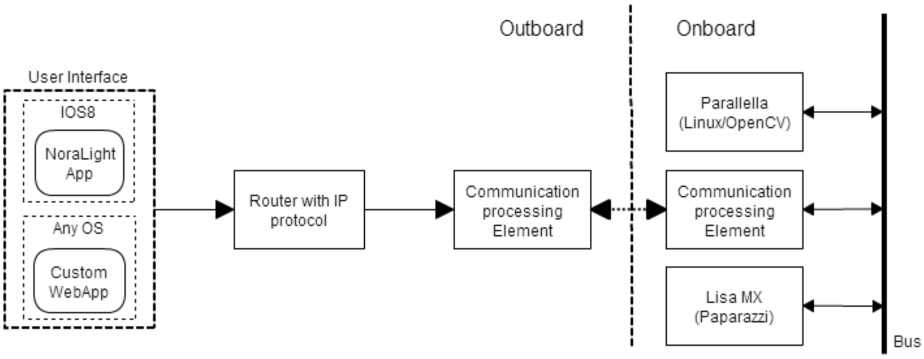


Figure 8.11: Software Diagram

Although software prototyping was done with tools such as Matlab and Python, it is known that these are not meant for the design of production software in the UAV. Therefore *Nora* will consist of modified open source software packages. In general, Linux is considered the best option with its high reliability and scalability in addition to the free and open-source availability. The software diagram can be found in Figure 8.11. A free and open-source flight controller is Paparazzi, with a Kalman filter and PID controller already available. Next to that, the software supports navigation through way-points and a lot of other useful functions. Paparazzi is maintained by an active community of which the MAVlab of the Faculty Aerospace Engineering from Delft University of Technology is one of them. Detection required a system with a large real-time computational capacity. OpenCV was considered a great option with visual detection libraries readily available and being free. Combined with a Linux based operating system on the processor side of the Parallella board for non real-time tasks, the complete detection processing can be done at maximum efficiency. To distribute communication flows via the different communication systems, a controller will be used to direct data flows on the UAV side of the UAS. The ground side of the system will have a comparable controller, before the acquired data is sent to the router. On ground a router will be used to send data locally by using an internet protocol (IP). IP is used to make the local network scalable, since it is a widely used standard for computer networks. The router may be running OpenWRT (a Linux distribution) for the handling of these protocols. From the operator's point of view, a simple user interaction is key, something Apple is famous for. Therefore the primary device for operations will be a tablet. The tablet allows the operator to start quickly with operating, to insert commands with a touch of a finger and with the ability to view all information on a large 24.6cm screen. To protect the console's hardware, a Survivor case from Griffin can be used[36]. This will allow the console to be less vulnerable for influences of its environment. Control software will be developed specifically for the tablet, to maximize performance of the console. Of course it might be the case that other hardware is already owned by the SAR-team or the system does not want to use the proposed system. These systems will be able to use a web application to have the same functions. The downside of using a web application will be the response graphical response of the console, which is considered to be lower in the browser. In the future more platform specific applications can be developed.

8.4.1 Data Handling Hardware Components

The following Table 8.7 describes the necessary hardware to accommodate for the proposed data communication structure as described in Figure 8.11. The data handling, or internal communication subsystem, also accounts for custom Printed Circuit Boards (PCBs) and all the wiring. These values are based on percentage assumptions of the total mass and power. The cost is based on the size of the subsystem. For the wires this equals the length times price per length. And for the PCBs, this equals the area times a unit price, assuming a 4 layer PCB. For the storage of all data, the logs of *Nora* but also all the detected

[36]iPad case, URL http://griffintechnology.com/survivor, [cited 24 June 2015]

images, need to be arranged. This can be done by two solid stated drives (SSDs), one for the storage of datalogs as a sort of flight recorder and the other as directly accessible memory. Although the connector on the SSDs will be SATA, the custom PCBs and wires will also account for this custom connector.
For the data handling the location of the connections are also of major importance. Therefore a duct system will be developed for inside the fuselage. Not only will these ducts host the cables and make these accessible, it also supports the connection of all subsystems inside the vehicle to the fuselage's structure. The right duct of the vehicle will host all USB ports that are linked to the main USB Hub Controller. The left duct will be used for all other cables such as power cables to the engines, but also the sensor signal cables. Large holes will be located in the duct for easy accessibility. To minimise electromagnetic field interference of different systems, the ducts and the cables will be shielded.

Table 8.7: Data Handling Component Budget Breakdown

Part	**Specification**	**Price [€]**	**Mass [kg]**	**Power [W]**
Custom PCB's	TBD	25	0.2	unknown
Wires	TBD	25	0.072	0.0125
USB Type-C Hub Controller (x5)	TUSB8041 Four-Port USB 3.0 Hub	77	0.025	unknown
SSD (2x)	SanDisk U110 SSD	180	0.003	0.007 (max. 0.625)
Total		**307**	**0.303**	**0.0265 (max. 1.2625)**

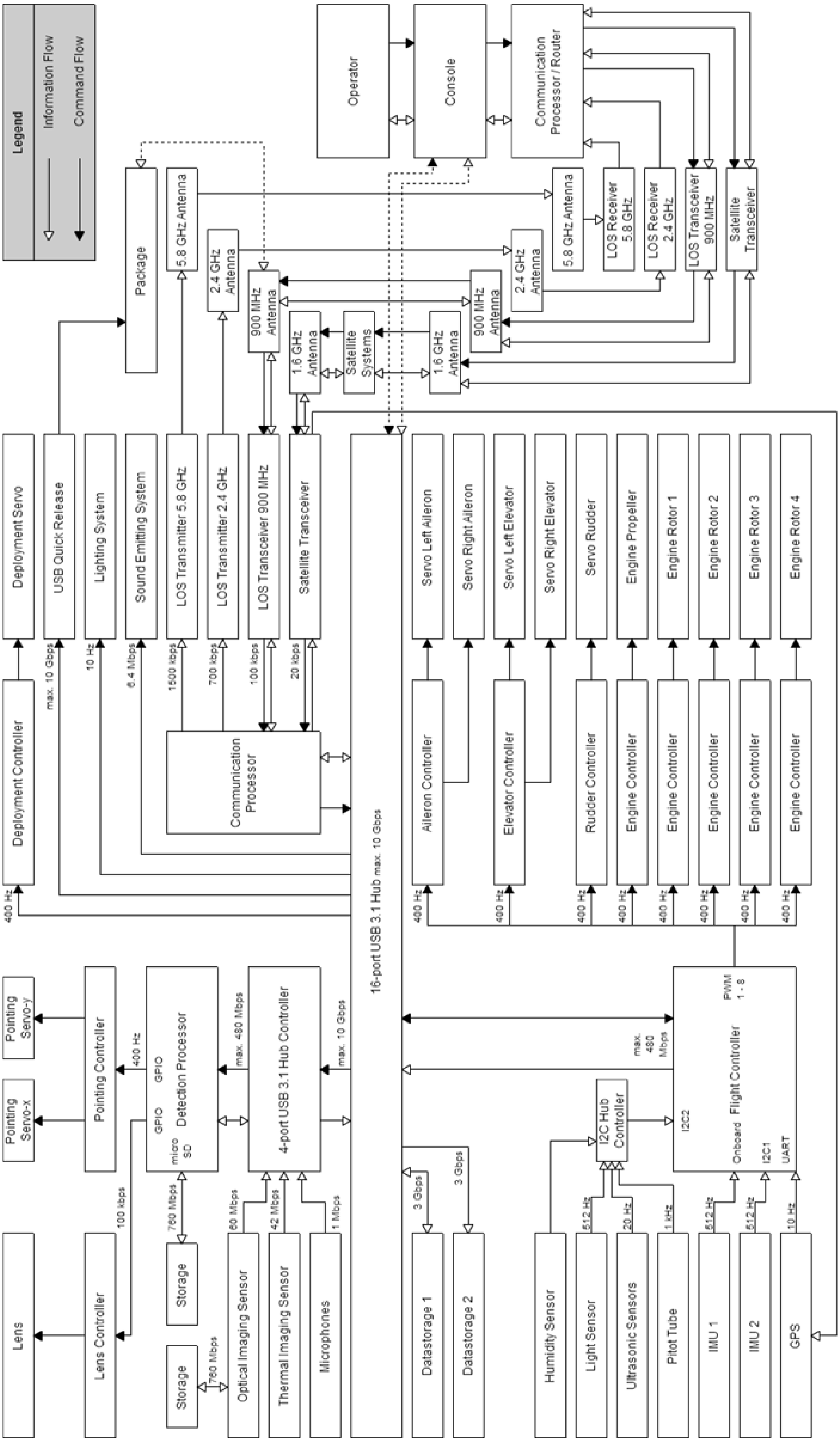


Figure 8.12: Communication Flow Diagram of the UAS (the Different Subsystems and their Links are indicated with Boxes and Arrows. The Data travels in the Direction of the Arrow.

9 | Preliminary Vehicle Design

The technical design of *Nora* is divided into the different disciplines of engineering. The process to come to a preliminary vehicle design was highly iterative. Close communication between the different disciplines is necessary to integrate all subsystems into a coherent and successful design. The integration of subsystems was aided with the use of Catia and a proprietary simulator. Section 9.1 discusses the simulator which was used to simulate the technical performance of the subsystems working together. Section 9.2 elaborates on the aerodynamic design. Following the aerodynamics is the power and propulsion subsystem in Section 9.3. The stability and control considerations of *Nora* can be found in Sections 9.4 and 9.5 respectively. The entire structural design and material choice is described in Section 9.6. Then the final layout is shown in Section 9.9. Finally the package design is discussed in Section 9.7.

9.1 Simulator

A simulator was made such that the movement of *Nora* could be simulated. This is an essential item to test the control system, stability of the aircraft, the aerodynamic model and the power and propulsion characteristics. In this section the simulator and its use will be explained.

9.1.1 Simulator Layout

The simulator consists of different parts which all have to communicate with each other. This can be seen in Figure 9.1. First the aircraft parameters, initial conditions and mission profile are defined, then the loop can start. The loop is run until the mission is completed. In the loop there is a gust generator which simulates possible gusts. The intensity of the gusts can be altered. A sensor simulation is needed as the control system needs some data in order to control *Nora*. With the sensor data the control system calculates the required torques on each of propellers and the required control surface deflections. These torques and deflections are then used as an input in the power and propulsion model and the aerodynamic model. These two models give all the forces and moments around the aircraft center of gravity. These forces and moments are then used to update the state variables such as position, velocity, acceleration, roll angle, pitch angle and yaw angle. Once the mission is finished, all relevant data is plotted such that the mission can be analysed. An example of this can be seen in Figure 9.3. In this example a simple climb during hovering is performed and then stationary hovering at that place. Optionally, one can visualise the mission which was just performed. In this visualisation VPython is used to show *Nora* flying in a landscape. The landscapes are generated using real life height data but the trees which are added are random. This visualisation is only used for presentation purposes. An example of this can be seen in Figure 9.2. In this example a part of the Dolomites is used for visualisation of the mountains.

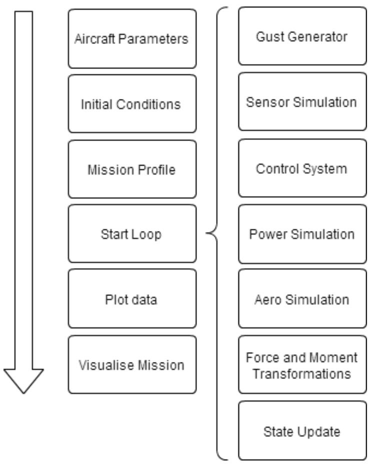


Figure 9.1: Simulator Flow Chart

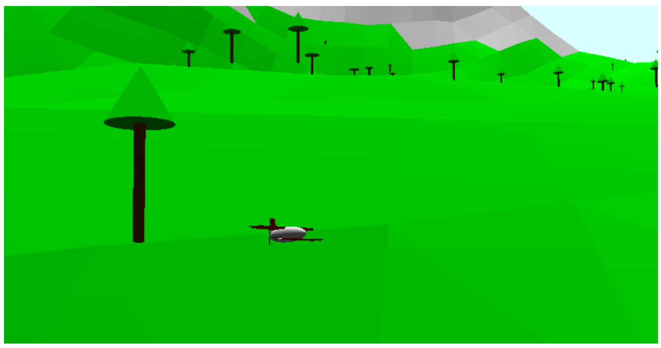


Figure 9.2: Simulator Visualisation

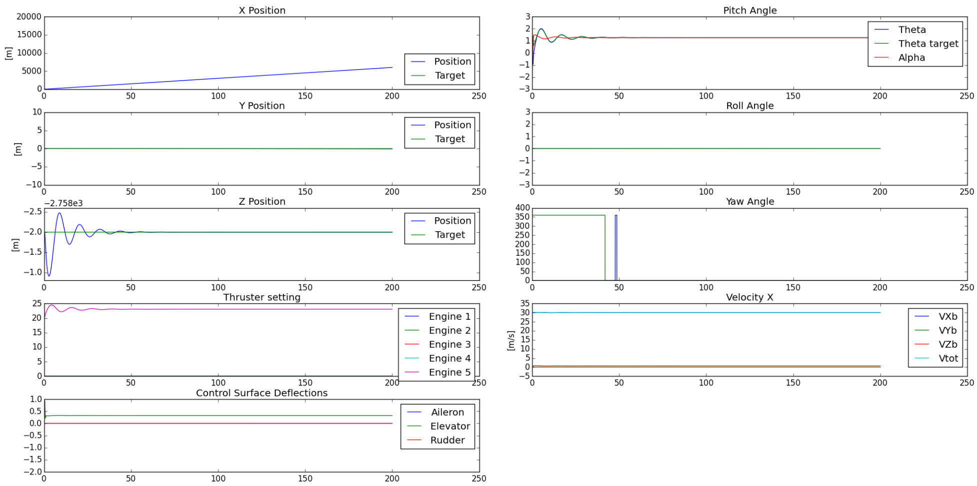


Figure 9.3: Example of Simulator Data Plots

9.1.2 Simulator Usage

As mentioned before, the simulator is mainly used to test the control systems and the interaction between different subsystems. The simulator is mainly used to test performance characteristics of the drone. Analytical methods to determine the performance of an aircraft often relies on a lot of assumptions which are not necessary in the simulator. In the simulator there is a power and propulsion model which simulates the power and thrust of the propellers. With the power calculated, one can check if there is enough fuel on board to fulfill the required mission and if the accumulator sizing is done correctly. An analytical estimate of the power used is not entirely correct, as a lot of corrections during hovering have to be made, which all require some extra power. Therefore the analysis of the power required is completed using the simulator.

9.2 Aerodynamics

As described in Chapter 6, the final configuration that was chosen for *Nora* was a tandem wing hybrid configuration with four hover propellers. Thus, for the majority of the mission, *Nora* will be in horizontal flight, generating lift with her wings. Proper aerodynamic design is therefore crucial. In this section, the aerodynamic design procedures are elaborated. Optimisation was performed for flying at $3000m$ altitude, because it was found from height maps that mountainous regions are rarely below $1000m$. *Nora* has to be able to fly up until $5000m$, therefore $3000m$ is the mean flying height. Firstly, the design of the planform layout is discussed followed by the closely related airfoil selection. Subsequently, the body size and shape determination are covered, after which the sizing of the vertical stabiliser is outlined. This is followed by the sizing, placement and actuation of the control surfaces. Finally, the implementation of aerodynamic performance into the simulator is described shortly, together with an assessment of additional parasitic drag due to flow disturbing objects attached to the vehicle.

9.2.1 Planform Design

To provide *Nora* with a mission endurance of two hours, the cruise phase is considered to be the the most critical flight phase during detection. This phase is dominant in terms of energy consumption in the mission profile of *Nora*. Therefore, the planform design is optimised for drag reduction in cruise flight. Moreover, *Nora* does not take off or land using its wings, so the wings could be optimised for efficient cruise flight. The process that was followed to come up with the most efficient design is described in this subsection. First of all, the main functions and constraints of the wing planform will be discussed. Secondly, the overall design methodology will be treated, followed by the starting point in the design. Finally, the optimisation process will be explained, with the eventual planform design as the final result.

Main Functions & Constraints

The main function of the planform for *Nora* is lift generation in cruise flight. Enough lift has to be provided to maintain cruise flight as well as to execute the required manoeuvres on high altitudes. The planform's second function comes from the earlier design phases. As indicated in Section 6.6.2, the final design outline chosen for *Nora* is a tandem wing configuration, to have the four rotors for vertical flight supported by the wing structure.

Next to the fact that the wings have to fulfill these main tasks, the outline of the planform is heavily constrained in various ways. The most important factors that constrain the design are:

- *Maximum span restriction*: by requirement MH-SYS-13, the maximum span is restricted to $1.5m$.
- *Rotor placement*: the rotors providing lift in hover mode have to be accommodated in the span. Since the rotors have a considerable diameter of $0.3m$ each, the placement should distort the flow around the wing as little as possible.
- *Aircraft stability*: to decrease the complexity of and burden on automated flight control as much as possible, longitudinal and directional stability would be highly preferable.

Design Methodology: *Weissinger's Approximation*

As mentioned in the previous paragraph, the planform would be primarily designed for optimal aerodynamic efficiency. To optimise the relative size and placement of the two wings for lift over drag performance, their interaction was firstly quantified using rectangular wings as a simple, first order model. Weissinger's approximation was used to find this interaction between the lift of both wings [25]. In this method, each airfoil is modeled as a flat plate and the lift of each airfoil is modeled as an irrotational vortex (Equation 9.1).

$$V = \frac{\Gamma}{2\pi r} \tag{9.1}$$

The location of the vortex and the control point on each airfoil are chosen to be quarter chord and three-quarter chord, respectively. This is carefully derived by Mason.[26] A total overview of the biplane geometry is given in Figure 9.4.

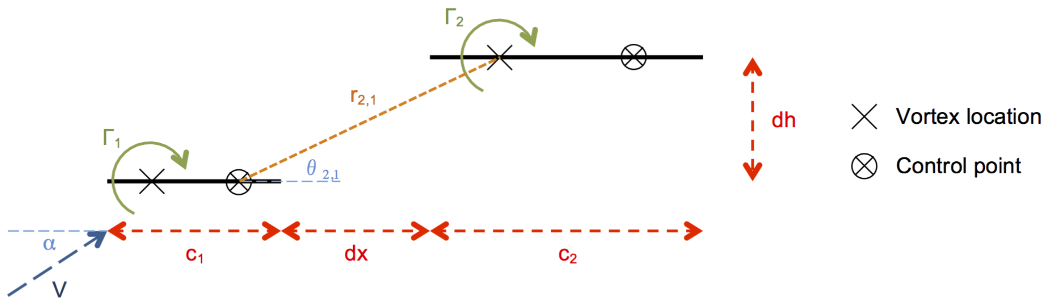


Figure 9.4: Tandem Wing Weissinger Approximation

The total system is described by two vortices:

$$V_{y,1} = \frac{\Gamma_1}{2\pi r_{1,1}}\cos(\theta_{1,1}) - \frac{\Gamma_2}{2\pi r_{2,1}}\cos(\theta_{2,1}) \tag{9.2}$$

$$V_{y,2} = \frac{\Gamma_2}{2\pi r_{2,2}}\cos(\theta_{2,2}) + \frac{\Gamma_1}{2\pi r_{1,2}}\cos(\theta_{1,2}) \tag{9.3}$$

For these vortices, the geometrical parameters can be worked out further, as given by the following relations:

$$r_{1,1} = \frac{1}{2}c_1 \quad (9.4) \qquad r_{2,2} = \frac{1}{2}c_2 \quad (9.5) \qquad \theta_{1,1} = \theta_{2,2} = 0 \quad (9.6)$$

$$r_{2,1} = \sqrt{\left(\frac{1}{4}(c_1 + c_2) + dx\right)^2 + (dh)^2} \quad (9.7) \qquad \theta_{2,1} = \frac{dh}{\frac{1}{4}(c_1 + c_2) + dx} \quad (9.9)$$

$$r_{1,2} = \sqrt{\left(\frac{3}{4}(c_1 + c_2) + dx\right)^2 + (dh)^2} \quad (9.8) \qquad \theta_{1,2} = \frac{dh}{\frac{3}{4}(c_1 + c_2) + dx} \quad (9.10)$$

Finally, the boundary condition of Weissinger's approximation could be applied to the system, which is given by

$$V_1 = V_2 = V_\infty \sin \alpha \quad (9.11)$$

With this condition, the system could be solved for the circulations Γ_1 and Γ_2, given all the geometrical and flight parameters. These results could then be used to compute lift performance of the airfoil, as in Equation 9.12

$$C_L = \frac{2L}{\rho V^2 S} = \frac{2\rho V b(\Gamma_1 + \Gamma_2)}{\rho V^2 bc} = \frac{2(\Gamma_1 + \Gamma_2)}{Vc} \quad (9.12)$$

Secondly, an estimation of the drag performance could be made, followed by the aerodynamic performance

$$C_D = C_{D,0} + C_{D,i} = C_{D,0} + \frac{C_L^2}{\pi A e} = C_{D,0} + \frac{C_L^2}{\pi \frac{b}{c} e} \quad (9.13)$$

$$Aerod.\, eff. = \frac{C_L}{C_D} \quad (9.14)$$

Starting Point & Design Variables

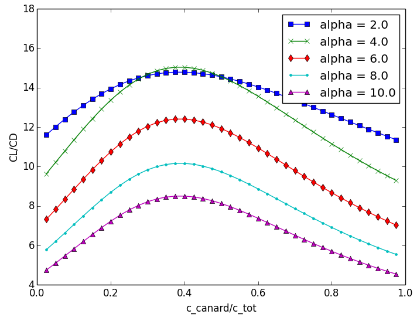
As can be seen in Figure 9.4 and its governing equations, the interaction of the airfoils is dependent on several geometrical quantities. By varying the geometrical parameters that describe the tandem wing system, the overall performance could then be quantitatively assessed to find the optimal configuration. The variables over which the configuration was changed, were

- Canard percentage of total chord c_c/c_{tot}
- Horizontal gap **dx** (if constant, set to $0.4m$)
- Vertical gap **dh** (if constant, set to $0.25m$)
- Angle of attack α (if constant, set to $2°$)

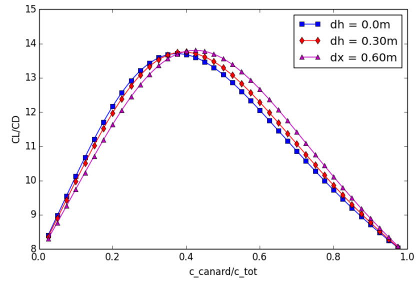
Other parameters were held constant throughout the design process because of the constraints given before, or to make a good comparison between the different concepts.

- Total planform length: $dx + c_w + c_c = 1.25m$
- Wing span: $b = 1.5m$
- Flight parameters: $V = 30ms^{-1}$, $\rho = 0.91kgm^{-3}$
- Zero-lift drag and Oswald efficiency factor: $C_{D,0} = 0.01$ and $e = 0.85$

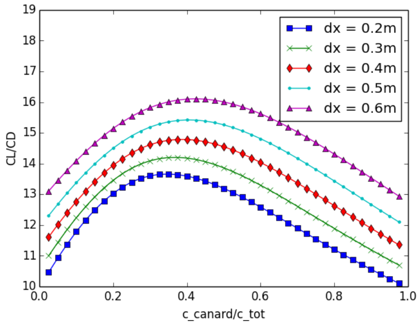
The tandem wing design was now assessed for variations in each parameter. To do so, a neutral starting configuration was chosen with a total chord length of $0.8m$ and a gap length of $0.45m$. The variation over each parameter was then observed. The results are given in Figure 9.5.
As can be seen from these graphs, the gap size has a major influence on the overall performance of the planform. This is partly caused by the fact that the total chord length is scaled down with increasing gap size to stay within the length requirement. This has a significant effect on the aspect ratio of the wing,



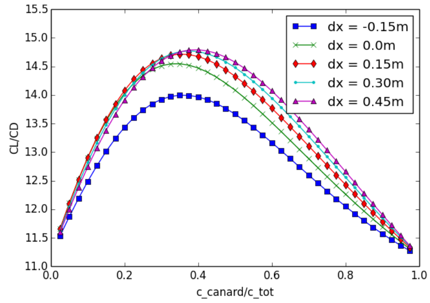
(a) Angle of Attack



(b) Vertical Gap



(c) Horizontal Gap (constant planform length)



(d) Horizontal Gap (constant chord length)

Figure 9.5: Effect of Several Parameters on Aerodynamic Efficiency

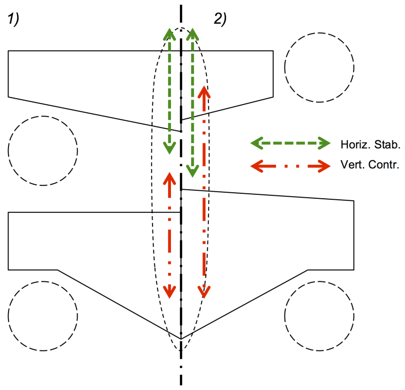
which in turn greatly influences the aerodynamic efficiency. Would the gap size be increased independent of the total chord, the effect would be much smaller and be inverted as shown in the second subfigure. Moreover, the angle of attack is also important for the aerodynamic efficiency of the wings. The highest optimum is however also determined by the airfoil and can therefore only be found at a later stage. Finally, the height difference is shown to have a minor but present effect on the aerodynamic efficiency. Note that a negative height difference gave exactly the same results as its positive counterpart, and is therefore omitted from the graph for clarity.

Design Iterations & Optimisation

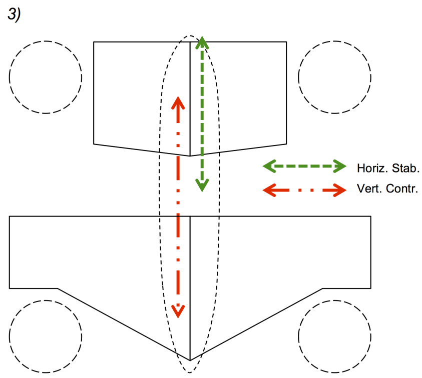
Obviously, the first design with identical wings for both the canard as well as the aft wing was not necessarily optimal. As could be derived from the qualitative plots of Figure 9.5, the optimum for the distribution of chord is always around 36-40% c_c/c_{tot}. Moreover, increasing the gap size by increasing the height difference is in general better for the aerodynamic efficiency. To fulfill the main requirement of the planform, which is creating lift to sustain level flight, a design total planform area of approximately $1.0m^2$ was deemed necessary to generate the required lift. With this area, the design lift coefficient would be 0.265, as given by Equation 9.15

$$C_{L,des} = \frac{2W}{\rho V^2 S_{des}} \tag{9.15}$$

A first design that was proposed, consisted of a smaller front wing and a larger rear wing with the ratio of chords $\frac{C_c}{C_w} = \frac{2}{3}$ as found to be optimal in the previous paragraph. Both wings would be extended to the maximum span of $1.5m$, with the rotors behind them to avoid disturbance of the flow. Finally, the vertical offset of the wings would be maximised, as this increased the aerodynamic efficiency of the system. Moreover, making the vertical gap as large as possible minimised the disturbing effect of the front rotors on the aft wing. This first iteration of the tandem wing system was however found to be either horizontally unstable or vertically uncontrollable, as can be seen in Figure 9.6a. The specific method for these calculations can be found in Section 9.4.
To solve these stability issues, its was decided that the front rotor placement had to be changed to the side of the canard. This change provided a major additional controllability margin in the front of the



(a) First & Second Iteration



(b) Third Iteration

Figure 9.6: Planform Design Iterations

aircraft. However, the overall planform area was reduced by approximately 10%. To compensate for this loss in area, high camber airfoils that generate a high amount of lift were elected, as described in Subsection 9.2.2. This planform could now be designed longitudinally stable, which was achieved by slightly lowering the canard chord to total chord ratio. However, one major downside of high camber is the high negative aerodynamic moment that it creates. Upon inspection, this moment turned out to be too large to overcome by the surface area available for the elevator, making *Nora* untrimmable.

As a result, another design iteration had to be done. In this iteration, the planform area was increased again, mainly by increasing the canard chord. This came with the cost of a slightly lower aerodynamic efficiency. This can be seen in Figure 9.7, where the red dots indicate the final aerodynamic efficiency achieved in each section. Together with the selection of a lower cambered airfoil, this caused the aerodynamic moment to go down to a much more acceptable level, though. With these adaptations, the planform was made longitudinally stable, controllable as well as trimmable. Therefore, this planform design was elected for *Nora*.

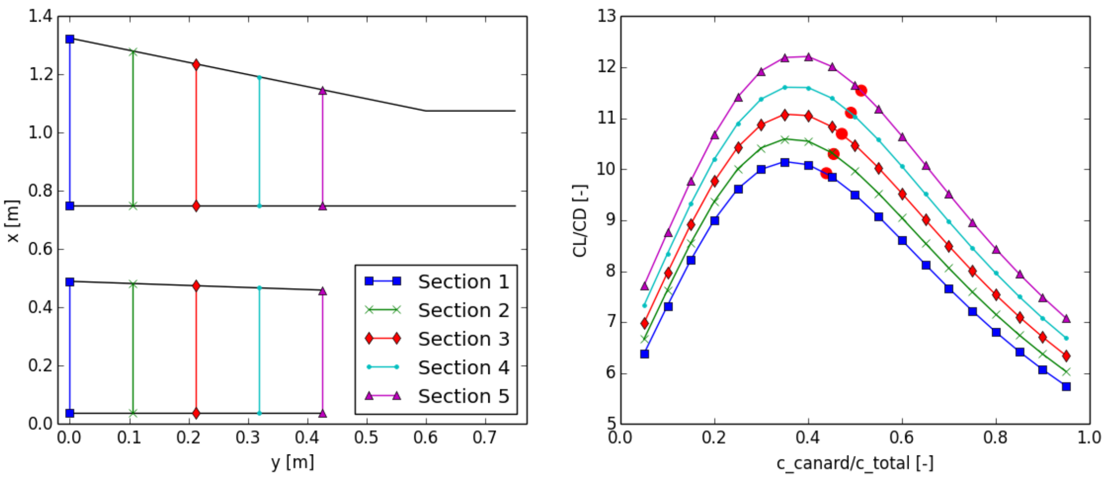


Figure 9.7: Final Planform Aerodynamic Efficiency

9.2.2 Airfoil Design

An important factor for the overall performance of the planform is the selection the airfoils for the main wing and the canard. To calculate the performance of the wings with certain airfoils the program XFLR5 was used. This is a program which models the lift, drag and many more performance parameters for both the 2D and 3D case. In the same way as for the planform design, the airfoils are designed for optimised drag reduction in cruise flight at $3000m$ altitude.

First the planform, as was sized in Subsection 9.2.1, and a preliminary body were modelled in XFLR5. Then a few starting airfoils were selected from reference aircraft.[1], [2], [3]. These airfoils were then slowly adjusted in thickness and camber. From all these options the option with the highest $\frac{C_L}{C_D}$ at the required angle of attack (due to required lift) was selected as airfoil combination. This appeared to be the NACA 6415 for the main wing and the NACA 4415 with 3 degrees twist for the canard. Thinner airfoils were not preferred as thicker airfoils can accomodate a lighter structure.

At this point it was not known that a C_m of -0.14 (which was the case for this airfoil selection) was far too large to overcome for such a small air vehicle. When designing the elevators it became clear that the elevators could never trim such a large moment. Therefore the canard should be designed bigger and/or the airfoils should be chosen differently. It appeared that airfoils with a high camber (the first digit of the NACA-4 digit series) have a better C_L and $\frac{C_L}{C_D}$ performance, but induce large negative moments. Therefore the the camber was lowered. Because this produces less lift also the planform size was adapted, see Subsection 9.2.1. Now it came out that the NACA2415 was the best for both wings. The installed angle of attack should be $-0.75°$ for the main wing and $4.5°$ for the canard. This airfoil choice has a lower but still acceptable $\frac{C_L}{C_D}$ at the required lift. It is stable and has only a small C_m to overcome, see Table 9.1 and Figure 9.9.

Table 9.1: Final Airfoil Design

Parameter	**Final Selection**
Main wing airfoil	NACA2415
Main wing twist [deg]	-0.75
Canard airfoil	NACA2415
Canard twist [deg]	4.5
Aircraft $\frac{C_L}{C_D}_{max}$	11.4
C_{m_α} [1/deg]	0.0018
Required C_L (due to planform area)	0.26

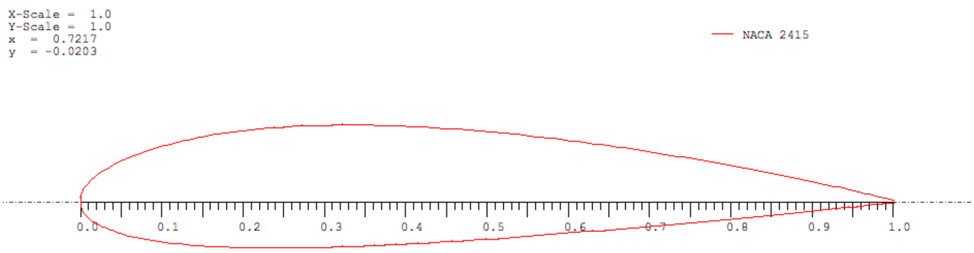


Figure 9.8: NACA 2415

9.2.3 Body Design

The preliminary body, as was used for airfoil selection, was adjusted many times and finally resulted in the end body, which can be found in Figure 9.10. It seems rather large for such a small drone. However, real drones have curves. Moreover, it could not be smaller due to all the payload that has to be carried along. The body length was limited by the span requirement as was the planform since the same reasoning

[1]Experimental Aircraft, URL `http://exp-aircraft.com/library/heintz/airfoils.html`,[cited June 15 2015]
[2]Apollo, URL `http://www.apollocanard.com/4_airfoil%20design.htm`, [cited June 14 2015]
[3]Airfoil Database, URL `http://m-selig.ae.illinois.edu/ads/coord_database.html#N`, [cited June 15 2015]

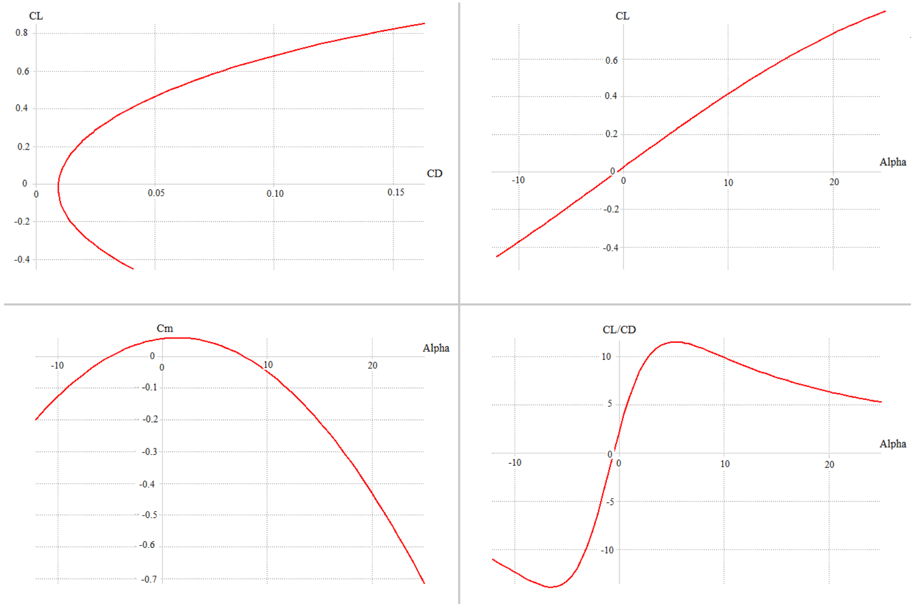


Figure 9.9: Lift, Drag and Moment Polars of Final Configuration (including planform, body & airfoils)

is applicable: it has to be able to take of in an foliaged environment, therefore the span can not exceed $1.5m$. Thus to achieve the needed volume, the body needed to be a bit thick and high. The minimum thickness was decided by the dimensions of the rescue package. Since for aerodynamic reason it is better to have a thinner body, this minimum thickness is the thickness chosen. Furthermore the aft part of the body is shaped in that round form, so the rotor (which is placed at the very rear) would be at the same height as the center of gravity, making sure it will not cause a (high) moment.

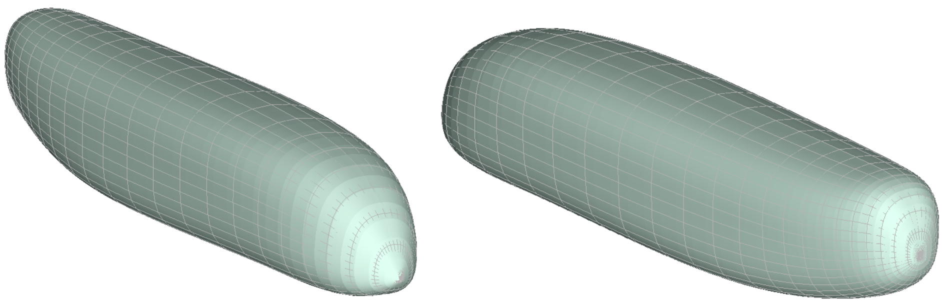


Figure 9.10: Body Shape (left: skew front view, right: skew back view)

9.2.4 Sizing of Vertical Stabiliser

In the three previous subsections the planform, airfoils and body were designed. However, the UAV also needs a vertical stabiliser for directional stability. Firstly the configuration and airfoil are selected. Secondly the vertical stabiliser is sized.

There is chosen for a single vertical tail on top of the body, because Roskam states that this is most beneficial for airplanes in the low subsonic speed range with respect to weight and aerodynamics.[27] This single vertical stabiliser still needs both an airfoil and dimensions. Torenbeek states that usually for a tail the airfoil is symmetric with a thickness ratio about 12% [28]. Multiple other reference aircraft have NACA0009 or NACA0012 airfoils for their vertical tails. Because the tail will be small, a thicker tail will be beneficial due to structural efficiency in thick structural members. Therefore for this vertical tail the NACA0012 is chosen, as can be seen in Figure 9.11.
Now the vertical stabiliser must be sized. This is done by a method given by J. Roskam based on the determination of the value of the directional stability coefficient, C_{n_β}. The formula for C_{n_β} is given in

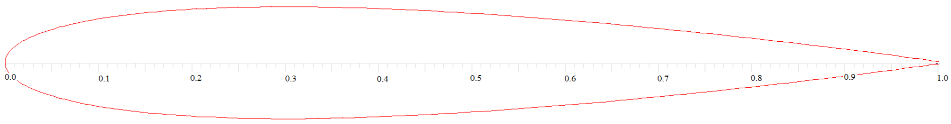


Figure 9.11: NACA 0012 Airfoil

equation 9.16 [29].

$$C_{n_\beta} = C_{n_{\beta_{wf}}} + C_{L_{\alpha_v}} \frac{S_v}{S} \frac{x_v}{b} \tag{9.16}$$

where $C_{n_{\beta_{wf}}}$ is the directional stability coefficient component due to the wing and fuselage, $C_{L_{\alpha_v}}$ the lift gradient of the vertical tail, S_v the vertical tail surface and x_v the distance between the center of gravity and the aerodynamic center of the vertical tail. The Equations for $C_{n_{\beta_{wf}}}$ and $C_{L_{\alpha_v}}$ can be found in Equations 9.17 and 9.18 respectively [30].

$$C_{n_{\beta_{wf}}} = C_{n_{\beta_w}} + C_{n_{\beta_f}} = C_{n_{\beta_f}} = -57,3 K_N K_{R_l} \frac{S_{fs} l_f}{Sb} \tag{9.17}$$

where S_{fs} is the side area of the fuselage. $C_{n_{\beta_w}}$ can be assumed to be zero for preliminary design. K_N, a factor accounting for wing-fuselage interference with directional stability, and K_{R_l}, the wing-fuselage directional stability factor, were found from *Airplane Design VI* [30].

$$C_{L_{\alpha_v}} = \frac{2\pi A_{v_{eff}}}{2 + (\frac{A^2_{v_{eff}} \beta^2}{k^2}(1 + \frac{tan^2(\Lambda_{\frac{1}{2}})}{\beta^2}) + 4)^{\frac{1}{2}}} \tag{9.18}$$

where $A_{v_{eff}}$ is the effective vertical tail aspect ratio and $\Lambda_{\frac{1}{2}}$ the half chord sweep angle. Formulas for calculating k, β and $A_{v_{eff}}$ can be found in Equations 9.19 to 9.22.

$$k = \frac{C_{l_{\alpha_{atM}}}}{\frac{2\pi}{\beta}} \tag{9.19}$$

$$C_{l_{\alpha_{atM}}} = \frac{C_{l_{\alpha_{atM=0}}}}{\beta} \tag{9.20}$$

$$\beta = (1 - M^2)^{\frac{1}{2}} \tag{9.21}$$

where $C_{l_{\alpha_{atM=0}}}$ is the 2D lift gradient of the vertical tail airfoil.

$$A_{v_{eff}} = [\frac{A_{v_f}}{A_v}] A_v (1 + k_{v_h}([\frac{A_{v_{h_f}}}{A_{v_f}}] - 1)) \tag{9.22}$$

$\frac{A_{v_{h_f}}}{A_{v_f}}$ is the ratio between the aspect ratio of the vertical tail in presence of the fuselage and horizontal tail to that of only the presence of the fuselage. k_{v_h} is the ratio between the horizontal tail surface area and the vertical area. $\frac{A_{v_f}}{A_v}$ is the ratio of vertical tail aspect ratio in presence of the fuselage to that of isolated tail. All these ratios can be found in *Airplane Design VI* [30]. Furthermore attention must be paid to the fact that the A_v is calculated from the center-line of the fuselage and not from the surface.

Now all equations to determine the C_{n_β} are known, it is needed to set a target C_{n_β} value. From *Synthesis of Subsonic Airplane Design* [28] it is found that C_{n_β} lies between 0.04 and 0.10 for single-engine subsonic aircraft and between 0.10 and 0.25 for transport aircraft. The UAV has only a single engine in cruise, but must also carry a lot when compared to its total weight. Therefore C_{n_β} is set to be 0.10.

First a tail was sized by visual reference. It appeared however that this tail was too large. Therefore size parameters were adjusted multiple times until the right dimensions were found that resulted in a C_{n_β} of 0.10. In Table 9.2 the values for calculating C_{n_β} are found. On the left the parameters that are fixed due to the speed, altitude, main wing and body can be seen. The tail is sized for cruise at $30ms^{-1}$ at an altitude of $3000m$, the same as for the wing and canard. On the right the variable parameters for both the first estimation and the final outcome can be found. These values are of the part of the tail outside of the fuselage.

Table 9.2: Parameters for Vertical Stabiliser Sizing

Fixed Parameters

Parameters	Unit	Value
$\frac{A_{v_{hf}}}{A_{vf}}$	–	1.1
$\frac{A_{vf}}{A_v}$	–	1.3
k_{v_h}	–	1.13
K_N	–	0.0024
K_{R_l}	–	1.16
$Cl_{\alpha_{atM=0}}$	deg^{-1}	6.5
M	–	0.092
S_{fs}	m^2	0.37
l_f	m	1.4
b	m	1.5
S	m^2	0.64

Variables

Parameters	Unit	First estimate	Final tail
c_r	m	0.35	0.31
c_t	m	0.16	0.16
$\Lambda_{\frac{1}{2}}$	rad	0.20	0.20
b_v	m	0.32	0.37
x_v	m	0.56	0.50
C_{n_β}	deg^{-1}	0.13	0.10

9.2.5 Design of Control Surfaces

Manoeuvering and control are essential parts of *Nora*'s mission. Due to the precision operation and the often difficult weather conditions, proper control surfaces are vital for mission success. This subsection therefore elaborately describes the sizing, implementation and actuation of these control surfaces. The general method followed in sizing the controls is described by Sadraey in *Aircraft Design, A Systems Engineering Approach*[31]. First, the methods and procedures for sizing and placement of the aileron, elevator and rudder will be explained. This is followed by a concise overview of the resulting control surface geometries. Finally, the actuator system selection is described.

Ailerons

Ailerons provide *Nora* with the required lateral manoeuvrability by creating a lift differential between the wings on either side of the body, resulting in a moment around the x-axis. This, in turn, results in a rolling motion. To size the aileron, a target performance was first selected from literature. Secondly, ailerons had to be designed to match the requirement.

From the definitions listed in *Flight Control Systems* by Pratt, it was found that *Nora* falls under a Class I aircraft qualification, with a manoeuvring requirement of Category A, Level 1 [32]. From Sadraey, it was then found that the roll requirement would be to achieve a bank angle of 60° within 1.3s at stall speed [31].

To predict the rate of roll, the non-dimensional moment around the x-axis caused by a certain aileron deflection had to be found. This was done using equation 9.23, from Sadraey.

$$C_{l_{\delta_A}} = \frac{2C_{l_{\alpha_w}}\tau_A C_R}{Sb}\left[\frac{y^2}{2} + \frac{2}{3}\left(\frac{\lambda - 1}{b}\right)y^3\right]_{y_i}^{y_o} \tag{9.23}$$

In this relation, $C_{l_{\alpha_w}}$ indicates the main wing lift slope and τ_A is the aileron effectiveness, determined from Sadraey, Figure 12.12 which depends on the percentage of chord the aileron takes up.[31] With the aileron deflection moment coefficient, the dimensional moment caused by the aileron could be computed according to Equation 9.24.

$$M_{aileron} = C_{l_{\delta_A}}\delta_A \frac{1}{2}\rho V^2 Sb \tag{9.24}$$

From there, the steady state roll rate at maximum deflection and the bank angle at which that rate would be reached could be found as in Equations 9.25 and 9.26.

$$P_{ss} = \sqrt{\frac{2M_{aileron}}{\rho S_{tot} C_{D_{roll}} y_D^3}} \tag{9.25}$$

$$\Phi_{ss} = \frac{I_{xx}}{\rho S_{tot} C_{D_{roll}} y_D^3}\ln\left(P_{ss}^2\right) \tag{9.26}$$

Finally, the roll time could be determined according to the following Equations 9.27 and 9.28.

$$\dot{P} = \frac{P_{ss}^2}{2\Phi_{ss}} \quad (9.27) \qquad t_{roll} = \sqrt{\frac{2\Phi_{des}}{\dot{P}}} \quad (9.28)$$

By iterating over this analysis, it was found that ailerons from inboard $0.35m$ to outboard $0.55m$ with a aileron chord of 20% of the total chord was well enough to meet the roll requirement.

Elevator

For the elevator design the angular acceleration $\ddot{\theta}$ that the elevator produces is of main importance. To design for this two criteria must be met: the take-off rotation requirement and the longitudinal trim requirement. The first however is not needed for take-off since *Nora* is able to take off vertically. It is however still needed for rotation since the drone must suddenly change its height, for instance if it must dodge something. In *Aircraft Design: A Systems Engineering Approach* it can be seen that for highly manoeuvrable aircraft the angular acceleration is $10 - 20deg\ s^{-2}$ [31]. For semi-manoeuvrable aircraft it is from $10 - 15deg\ s^{-2}$. *Nora* must be somewhere in the middle between manoeuvrable and semi-manoeuvrable. Therefore the angular acceleration needed is set to $15deg\ s^{-2}$.

First we will start with the first requirement: the take-off rotation. First a free body diagram (FBD) was made applicable to *Nora*. This FBD can be found in figure 9.12. From this FBD Equations 9.29 to 9.31 were derived.

$$\ddot{\theta} = \frac{M + \delta_{L_c} x_c}{I_{yy}} \frac{180}{\pi} \quad (9.29) \qquad M_{ac} = \frac{1}{2}\rho V_{stall}^2 S C_{m_{ac}} \quad (9.30) \qquad \delta_{L_c} = C_{L_{\delta_{e_c}}} \delta_e \frac{1}{2}\rho V_{stall}^2 S_c \quad (9.31)$$

As can be seen V_{stall} is used, because at the stall speed the elevators have the least influence. Furthermore the moment of inertia I_{yy} and the coefficient $C_{m_{ac}}$ (calculated at the stall angle of attack) are found from the XFLR5 model. δ_e is the deflection of the elevator, this is still changeable as long as it is within reasonable range (up to 20°). $C_{L_{\delta_{e_c}}}$ is a coefficient found from *Airplane Design VI* [30]. All values used are found in Table 9.3. The dimensions of the elevator are used to some of the coefficients.

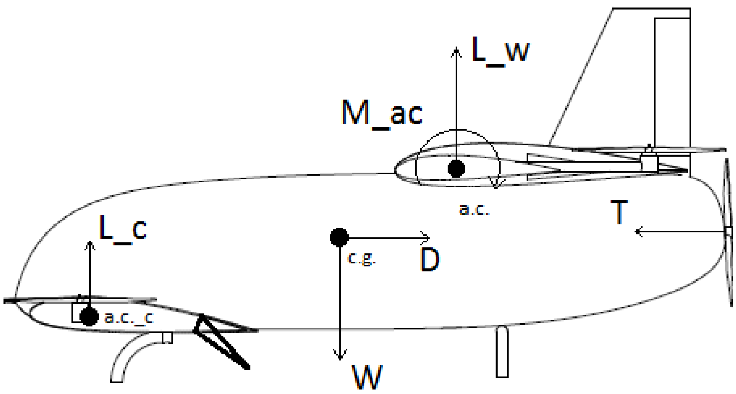


Figure 9.12: Free Body Diagram of *Nora* in Flight

Now the elevator still has to be designed for the longitudinal trim requirement. Again it starts with the FBD. Equations 9.32 and 9.33 are found from the FBD. Assumed is that the thrust works on the same line as the center of gravity, since the body is deliberately shaped for this, see Subsection 9.2.3. The moment must be zero to be trimmed.

$$L_w + L_c = W \quad (9.32) \qquad M = M_{ac} + L_c x_c - L_w x_w = 0 \quad (9.33)$$

In these equation the lift and moment components can be written as functions of their coefficients, see Equations 9.34 to 9.37.

$$L_w = \frac{1}{2}\rho V^2 S (C_{L_{0_w}} + C_{L_{\alpha_w}} \alpha) \quad (9.34)$$

$$L_c = \frac{1}{2}\rho V^2 S_c (C_{L_{0_C}} + C_{L_{\alpha_C}}\alpha + C_{L_{\delta_e}}\delta_e) \quad (9.35)$$

$$W = \frac{1}{2}\rho V^2 S C_{L_1} \quad (9.36)$$

$$M_{ac} = \frac{1}{2}\rho V^2 S\bar{c}(C_{m_0} + C_{m_\alpha}) \quad (9.37)$$

If these equations are filled in in Equation 9.32 and 9.33, the system can be rewritten in a matrix format, see Equation 9.38.

$$\begin{bmatrix} C_{L_{\alpha_w}} + C_{L_{\alpha_c}}\frac{S_c}{S} & C_{L_{\delta_e}}\frac{S_c}{S} \\ C_{m_\alpha}\bar{c} + C_{L_{\alpha_c}}x_c\frac{S_c}{S} - C_{L_{\alpha_w}}x_w & C_{L_{\delta_e}}x_c\frac{S_c}{S} \end{bmatrix} \begin{bmatrix} \alpha \\ \delta_e \end{bmatrix} = \begin{bmatrix} C_{L_1} - C_{L_{0_w}} - C_{L_{0_c}}\frac{S_c}{S} \\ C_{L_{0_w}}x_w - C_{m_0}\bar{c} - C_{L_{0_c}}x_c\frac{S_c}{S} \end{bmatrix} \quad (9.38)$$

If this matrix equation is solved it can be seen if the system can be trimmed. If the angle of attack is smaller than the stall angle and if the elevator deflection is smaller than the set maximum deflection, then the elevator is able to trim the aircraft. The values of the coefficients used and the values of the elevator parameters can be found in Table 9.3. The elevator in- and outboard location are given with respect to the fuselage center line.

Table 9.3: Parameters for Elevator Sizing

Coefficients and fixed parameters

Parameter	**Value**	**Coefficient**	**Value**
V_{stall} [m/s]	22	$C_{L_{\alpha_w}}$ [1/rad]	3.3
V_{cruise} [m/s]	30	$C_{L_{\alpha_c}}$ [1/rad]	1.4
$S[m^2]$	0.64	C_{m_α} [1/rad]	-0.074
$S_c[m^2]$	0.37	$C_{L_{\delta_e}}$ [1/rad]	1.0
$\rho_0[kg/m^3]$	1.225	C_{L_1} [-]	0.26
$\rho_{3000}[kg/m^3]$	0.91	$C_{L_{0_w}}$ [-]	-0.030
$\bar{c}$ [m]	0.44	$C_{L_{0_c}}$ [-]	0.15
x_w [m]	0.21	C_{m_0} [-]	0.0050
x_c [m]	0.51		

Elevator parameters

Parameter	**Value**
$\frac{c_e}{c_c}$ [-]	0.25
$y_i[m]$	0.18
$y_o[m]$	0.28
$\delta_{e_{max}}$ [deg]	20
$\delta_{e_{min}}$ [deg]	-20

Rudder

Similarly to the ailerons and elevator, the rudder was to be designed to provide a sufficient force and moment increase to navigate *Nora* through its limiting direction manoeuvring case. Again, this had to be achieved for a maximum rudder and aileron deflection of 20°. First of all, the limiting load case had to be determined. Secondly, the turning parameters had to be derived. Thirdly, control derivatives based on the preliminary rudder design were estimated from literature. And finally, the performance was tested against the limiting requirement, after which steps three and four were reiterated until a proper design was found.

Firstly, the limiting load case was determined. For a single engine aircraft there are four requirements for which one could design the rudder.

1. The aircraft must maintain alignment with the runway during a crosswind landing.
2. The aircraft must be able to oppose spin rotation and to recover from a spin.
3. The aircraft must be able to coordinate a turn.
4. The rudder must be able to overcome the adverse yaw that is produced by the ailerons.

Because *Nora* also has rotors, she will take off vertically and could use rotors during flight to recover from a spin. Therefore the first two requirements are irrelevant for this hybrid design. From Sadraey, it is found that the fourth requirement is automatically met when the system is designed for requirement number three. Therefore the rudder will be designed for the coordinated turn requirement.

In a coordinated turn, lateral force equilibrium must be applicable. This state is most critical to maintain at minimum turn radius at cruise. In that situation, a turn is made at $C_{L,max}$, resulting in a certain maximum bank angle found through Equation 9.39.

$$\phi = \arccos \frac{W}{L} = \arccos \frac{W}{C_{L,max}\frac{1}{2}\rho V^2 S} \tag{9.39}$$

From this bank angle, the steady-state pitch rate (Q_{ss}) and yaw rate (R_{ss}) could be determined (Equations 9.40 & 9.41). The moments that are required in roll and yaw to sustain the coordinated turn are found subsequently through Equations 9.42 and 9.43.

$$Q_{ss} = \frac{g\sin^2(\phi)}{V\cos(\phi)} \tag{9.40}$$

$$R_{ss} = \frac{g\sin(\phi)}{V} \tag{9.41}$$

$$L_{A_t} = (I_{zz} - I_{yy})R_{ss}Q_{ss} \tag{9.42}$$

$$N_{A_t} = I_{xz}R_{ss}Q_{ss} \tag{9.43}$$

With these equations, a balance in forces and moments for the coordinated turn could be set up. This balance is summarised by the matrix system of equation 9.44, with as final intention to solve this system for the maximum angles β, δ_A and δ_R, to feed back the maximum control surface deflections to the requirement.

$$\begin{bmatrix} C_{y_\beta} & C_{y_{\delta_A}} & C_{y_{\delta_R}} \\ C_{l_\beta} & C_{l_{\delta_A}} & C_{l_{\delta_R}} \\ C_{n_\beta} & C_{n_{\delta_A}} & C_{n_{\delta_R}} \end{bmatrix} \cdot \begin{bmatrix} \beta \\ \delta_A \\ \delta_R \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{2L_{A_t}}{\rho V^2 Sb} \\ \frac{2N_{A_t}}{\rho V^2 Sb} \end{bmatrix} - \frac{R_{ss}b}{2V} \begin{bmatrix} C_{y_r} \\ C_{l_r} \\ C_{n_r} \end{bmatrix} \tag{9.44}$$

The only unknowns left in this system are the control derivatives of the UAV in first matrix and the last vector. Estimations of these values are found through the equations and plots based on statistical data that are presented by Roskam in *Part VI* of *Airplane Design* [30]. Note that they are dependent on the chosen rudder geometry and were reiterated until a satisfactory solution emerged. The final results are listed in Table 9.4.

Table 9.4: Lateral Control Derivatives

Derivative	Value
C_{y_β}	-0.63
C_{y_r}	0.30
$C_{y_{\delta_A}}$	0
$C_{y_{\delta_R}}$	0.17

Derivative	Value
C_{l_β}	-0.15
C_{l_r}	0.16
$C_{l_{\delta_A}}$	-0.089
$C_{l_{\delta_R}}$	0.0043

Derivative	Value
C_{n_β}	0.10
C_{n_r}	-0.085
$C_{n_{\delta_A}}$	-0.0033
$C_{n_{\delta_R}}$	-0.058

After several iterations, the rudder was eventually determined to span from $0.25m$ until $0.40m$ measured from the body's centerline. Moreover, the maximum deflection was 20° as designed for and the chord was set to a constant value of $0.07m$, which is 20% of the average chord of the part of the tail where the rudder is situated. This was done in consultation with the structural design team to decrease structural complexity and therefore weight and cost.

Final Results Control Surface Sizing

In Table 9.5, the final results of the sizing of the control surfaces can be found.

Table 9.5: Final Control Surface Sizing

Control Surface	y_i $[m]$	y_0 $[m]$	Chord	δ_{max} $[deg]$
Aileron	0.35	0.55	20% c_w	20
Elevator	0.18	0.36	25% c_c	20
Rudder	0.25	0.40	$0.07m$	20

Control Surface Actuation

After their sizing, the control surfaces still needed actuation. This paragraph discusses the actuators that were selected to control the control surfaces. Since the torques and forces required to deflect the control surfaces are relatively small, it was chosen to use servos as actuators. These are very lightweight and cheap, but only have a limited range of achievable torques. The torques required to deflect the control surfaces were estimated at their absolute maximums. This means flying at sea level at the maximum speed and fully deflecting the control surfaces.

Additionally it is assumed that the lift increase is proportionally divided over the cord and that the lift change in the control surface acts at the quarter chord of the control surface. This results in heavily over-designed actuators, but this is beneficial to reduce the change of failure since they are not pushed to their limits.The results of the analysis as well as the selected servos and their weights and costs are listed in Table 9.6.

Table 9.6: Selected Servos

	Req. T [Nm]	Max. T [Nm]	Weight [g]	Cost [€]	Name
Elevator	0.28	0.29	17	5	Turnigy MX-331S
Aileron	0.58	0.73	32	16	HXT 9610
Rudder	0.16	0.17	9	3.50	Power HD-1900A

9.2.6 Aerodynamic Simulator Model

With the final design of the planform, airfoils, body and vertical tail, the aerodynamic performance of the vehicle could be found. To account for the correct mass distribution all the systems and loads inside the fuselage as well as rotors were modeled as point masses in and around the aircraft. By doing so, the correct inertias around all axes were incorporated into the analysis. With the Vortex Lattice Method of XFLR5, the overall force and moment coefficients in all three dimensions could then obtained, together with their point of application, for any flight condition.

This analysis was repeated, ranging over different values of the parameters α (-12° − 12°), β (-12° − 12°), V ($20ms^{-1} - 40ms^{-1}$) and ρ ($0.7kgm^{-3} - 1.3kgm^{-3}$). By doing so, *Nora*'s performance and behaviour could be interpolated at a wide range of conditions that were expected during normal operations. This interpolation was done by performing a linear least squares analysis for each coefficient as function of each of the four flight parameters. Correspondingly, the in-flight behaviour of *Nora* was modeled as function of her flight condition. This function was implemented in the flight simulator, which is discussed in Section 9.1, to test flight performance and tune the flight controller.

9.2.7 Parasitic Drag Estimation

To accurately predict the flight performance of *Nora*, the aerodynamic data obtained with XLFR5 had to be extended with estimates of the drag of the objects that are attached stationary to the vehicle. Main object that disturb the flow in horizontal cruise are the landing gear and the vertical rotors. Finally, the effect of the main wings in hover flight was also estimated.

Vertical Rotors (Horizontal Flight)

Modeling the drag of the vertical rotors was done using an extended model in XFLR5. Additional lifting surfaces were created to mimic the rotors and engines using symmetrical wing profiles. For the rotors, a relatively thin profile was used (NACA 0012) and for the electromotors, a relatively thick and blunt profile was employed (NACA 0024, with location of maximum thickness modified to 50% of chord). The model was analysed by XLFR5, after which the results were compared to the characteristics without rotor stand-ins. The analysis showed an increase in parasitic drag of 47.4%. The increase in lift and lift-induced drag was neglected, since the XFLR5 analysis used smooth airfoils that would significantly contribute to the overall lifting performance. The actual rotors on the other hand have a much more blunt shape and will most likely show much more separation and turbulence around their edges. This will be detrimental for the lift increase these elements cause.

Landing Gear (Horizontal Flight)

To accurately predict the drag of an aircraft's landing gear has proven to be very complex. To properly design a landing gear, aviation companies nowadays use extensive wind tunnel testing and detailed CFD modeling techniques to come to a good design. An estimation of the in-flight drag caused by the non-retractable landing gear was made with research from the *ADHeRo* project of the European Commission's Community Research and Development Information Service [33]. Using wind tunnel tests and CFD calculations, the researchers established that a non-retractable skid landing gear contributes 23% of the overall parasitic drag of the vehicle.

Parasitic Drag in Horizontal Flight

To come to the final zero-lift drag coefficient of *Nora*, the contributions of both the vertical rotors as well as the landing gear were added. Without alterations, the C_{D_0} was found to be 0.95 in cruise flight at the design speed of $30ms^{-1}$ and density of $0.91kgm^{-3}$. The final parasitic drag coefficient was found using Equation 9.45

$$C_{D_0,add.} = C_{D_0,orig}\left(\frac{1+perc_{vert.rot.}}{1-perc_{land.gear}}-1\right) = 0.095\cdot\left(\frac{1+0.474}{1-0.23}-1\right) = 0.087 \tag{9.45}$$

At every instance, this additional parasitic drag coefficient is added to the current drag coefficient to account for the presence of rotors and landing gear. This updated drag coefficient is used in the simulator for a more accurate flight performance estimation.

Ground Effect (Take-off & Landing)

The ground effect is a well known phenomenon within the aerospace industry. It applies to both winged aircraft as rotorcraft. Since during take-off and landing *Nora* will be in hover mode, only the rotorcraft round effect has to be considered.

First and foremost the induced velocity of the airflow is relevantly lower close to the ground. Due to this the resultant lift vector is ore vertical and the induced drag is lowered. This means that less power is required to provide the same amount of thrust. The second effect is the reduction of vortex creation at the tip of the rotors. This makes the outboard part of the rotors more efficient once again increasing the overall efficiency of the rotor. Overall this results in a 7% increase in lift at an altitude of half the propeller diameter as can be seen in Figure 9.13[4].

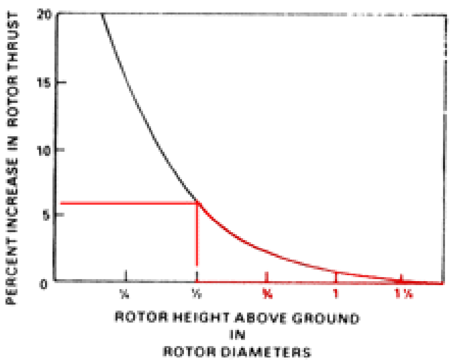


Figure 9.13: Ground Effect for Rotorcraft

The combined effect of the propellers on the wings in hover mode were considered in the same analysis. However it turned out that no research was available on this topic and therefore no accurate approximation can be made. The only interesting thing that can be mentioned is that the presence of the wings at the edges of the rotors results in a reduced tip vortex. This as explained before increases the efficiency of the rotors which is desirable. Further investigations of the effects have to be done in the future when the first prototype is available.

[4] Rotor Ground Effect, URL `http://www.copters.com/aero/ground_effect.html`

9.3 Power & Propulsion

The power and propulsion subsystem design has a number of components. First the general approach to the design is discussed, followed by the propeller design. Subsequently different power and propulsion concepts are proposed and one is chosen. Then the different components are discussed, namely the electric engines, combustion engine, the generator, the accumulator and the fuel. Then there is a short subsection on the heating and cooling followed by the layout of the power and propulsion subsystem. The section is concluded with a results and conclusion.

9.3.1 General Approach

In order to design the power and propulsion system of *Nora* some steps had to be taken. The propulsion was be done using propellers, so first some research concerning propellers was performed. In this research the link between thrust, power and rounds per minute (RPM) is found and the method used is explained. The propellers generate thrust if they are driven by an engine. If the required power is known, an appropriate engine can be chosen. The focus of the power and propulsion system is to make it as light as possible, but still producing enough power to support all systems. Once the engines are chosen, the sizing of the generator, accumulator and the fuel tank can be done. This process was done for different concepts, such that the different concepts can be compared against each other. The propellers and engines were chosen to be able to cope with limit loads. These limit loads were determined at $5000m$ where *Nora* should still be able to perform certain manoeuvres. The amount of energy that has to be stored in the accumulator and fuel tank was determined using the simulator. More details about the simulator can be found in section 9.1.

9.3.2 Propeller

Momentum theory and blade element theory[5] were used to calculate the propulsion characteristics in both horizontal and vertical direction. Momentum theory is generally used to determine the relationships between thrust (T), power (P) and induced velocity (V_i), and is based on energy and momentum conservation [34]. The dynamic thrust can be calculated using Equation 9.46. Here ρ is the density, V_{ac} is the aircraft velocity and A is the disc area equal to $0.25\pi D^2$.

$$T = 2\rho A V_i (V_i + V_{ac}) \tag{9.46}$$

However, it has to be emphasised that this theory is based on several assumptions. The most important assumption is the equality of the induced velocity with the pitch velocity. This assumption was used for conceptual calculations, but the equation can be optimised by using statistical data. Therefore, on the advise of expert Prof. M.D. Pavel, an empirical factor was added[6]. This factor was calculated using the data of 149 different combinations of propeller size and RPM. The factor is dependent of the propeller diameter and pitch and is shown in Equation 9.47. The pitch velocity is a velocity at which the propeller is cutting through the air. A comparison with a screw can be made, were the screw is cutting at a certain speed through the material per rotation.

$$T = \rho A (V_e V_e - V_e V_{ac}) \left(\frac{D}{3.29546 Pitch}\right)^{1.5} \tag{9.47}$$

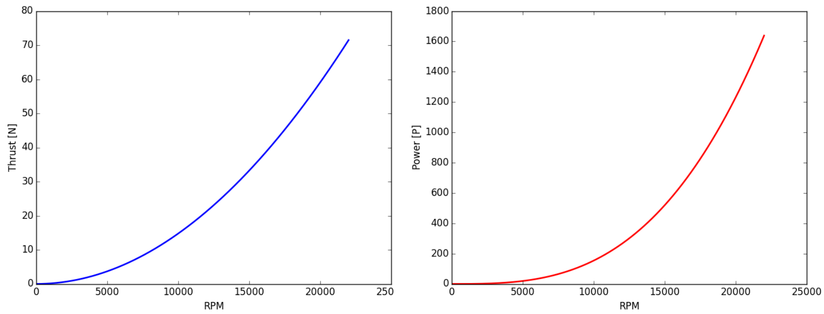
This equation was validated using test data. In this data the sizing of the propeller and the actual thrust at a certain RPM was given. On average the equation has an error of 1.87% and a standard deviation of 13%. The equation was validated for a diameter range from $12cm$ to $44cm$ and a pitch range from $5cm$ to $28cm$. Typical thrust ranges from $8N$ up to $60N$. One can conclude that the equation used is applicable for *Nora* and can be used in further calculations.

First the propellers for hovering will be determined. It is important that the power needed to hover is minimised while still being able to manoeuvre and fit the propellers in the drone planform. From the aerodynamics, the maximum propeller diameter was determined to be $30cm$. Because the vertical speed during hovering does not have to be very high, a low pitch can be used in order to reduce the power. This

[5] Blade Element Theory, URL `http://www.aerospaceweb.org/design/helicopter/element.shtml`,[cited 27 May 2015]

[6] Empirical factor, URL `http://www.electricrcaircraftguy.com/2014/04/propeller-static-dynamic-thrust-equation-background.html#.VW8wj1yqqkp` [Cited on 04/06]

resulted in a pitch of $5cm$ for all the hovering propellers. The design of the propellers is custom made and is shown in Figure 9.15. The propellers will be custom made because this allows further optimisation of the aerodynamic characteristics of the propeller. This also allows custom mounting of the propeller onto the engine. Custom made propellers can be very cheap as they can be 3D printed. The thrust and power characteristics of the propeller can be seen in Figures 9.14a and 9.14b.



(a) Hover Thrust vs RPM (b) Hover Power vs RPM

Figure 9.14: Hover Thrust & Power vs RPM

Figure 9.15: Custom Designed Propeller

Secondly, the propeller used for forward thrust has to be determined. For this propeller it is important that it has good high speed characteristics. This means that the pitch of the propeller will be increased. The diameter was set to be $40cm$ in order to reduce the power needed. The pitch was chosen to be $30cm$ to give good high speed characteristics. The design of the propeller was custom made and is shown in Figure 9.15. The thrust versus velocity characteristics given the maximum amount of power can be found in Figure 9.17.

9.3.3 Different Power & Propulsion Concepts

In order to power *Nora*, different options were available. In this subsection the different power and propulsion concepts will be explained and one of the concepts will be chosen. The first concept is a power and propulsion system where a combustion engine is connected to a generator which charges an accumulator and powers some systems. The accumulator can be used to accommodate for peak power demands. Four electrical hover engines will be used and one electrical engine for cruise flight. The first concept has mass of $2.45kg$

The second concept is almost the same as the first concept, but now the horizontal propeller is connected to the combustion engine directly. This saves one electric engine but adds a drive shaft. It has a mass of $2.35kg$

The third concept looks similar as the other two concepts, but is quite different. The horizontal propeller is connected to the combustion engine but no generator is connected to the combustion engine. An accumulator is used to power the hover engines during hovering, but is not charged anymore. In this concept there is no need for a generator, but the accumulator will be heavier pushing the mass to $2.9kg$

The last concept is the fully electric concept. In this concept no combustion engine is present anymore. Everything is powered by the accumulator which means that the accumulator will be heavier. This concept saves a combustion engine, fuel and a generator at cost of a heavier accumulator resulting in a mass of $7.9kg$

After comparing the concepts, concept 1 was chosen. It is not the lightest option, but the positioning of the combustion engine is in the front of the fuselage and the horizontal propeller is in the rear. This means a drive shaft should be going from the front to the rear which was not found to be feasible as the shaft would then have to run around the package. Therefore concept 1 was chosen.

9.3.4 Electric Engines

Electric engines will be used for *Nora*. The four engines used for hovering will be electrical, so the weight of the electrical engine is very important as it will be used multiple times in the drone. In order to chose the best engine, a list of more than 40 electrical brushless engines has been made. In this list the weight, maximum power and continuous power are given for each engine. A power versus mass plot is made for all the electric engines, this can be seen in Figures 9.16. The choice for brushless is made because of the good reliability and wearing characteristics of these motors. The brushless motors have a very good efficiency, low noise generation and high power to weight ratio. An alternative is the brushed electric engine which is easier to control and cheaper but it has lower power to weight ratio, requires more maintenance and is less efficient. Therefore the brushless engine was found to be the best option.

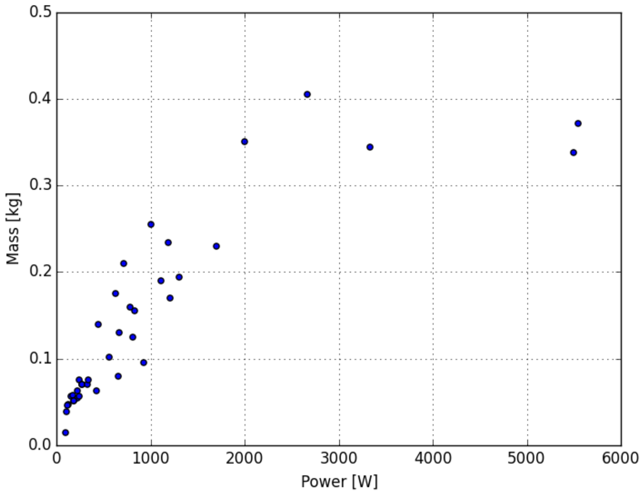


Figure 9.16: Electric Engines

First the hovering engines were determined. *Nora* needs to be able to accelerate $0.5g$ at highest altitude and has to be able to provide enough continuous power to keep the drone in the air at that altitude. These are the critical situations for the engines, so these will be used to choose the best engine. In Subsection 9.3.2 the conversion between the thrust and the power is explained. This method will now be used to find the required power that has to be provided by the engines. If the UAV has to be able to accelerate $0.5g$ it has to provide $162N$ thrust in total, using a mass of $11kg$. This means that each engine has to provide $40.5N$ thrust. Using the method explained before, this required thrust can be converted into a required power, which in this case is equal to $910W$. The continuous power needed is around $500W$. The lightest option that fulfils this requirement is the NTM Rotor Drive 450 Series which weighs only about $0.1kg$. This engine is chosen for all the hover engines.

Secondly the rear engine, which provides the horizontal thrust, is determined. The required thrust that needs to be provided by this engine heavily depends on the type of manoeuvres performed. From the simulation it is found that the rear engine has to be able to produce $40N$ of thrust in order to still be able to perform sharp turns and high climb rates. The thrust is dependent on the velocity therefore a velocity versus thrust curve is made in order to map the thrust over the whole velocity range. The NTM Rotor Drive 600 Series turns out to be the best option for the rear engine. It has a very high maximum ($5500W$) and continuous ($3300W$) power characteristics. The mass of the engine is $0.338kg$. The thrust map can be seen in Figure 9.17.

9.3.5 Combustion Engine

A combustion engine will be used to convert the fuel into electrical energy. The conversion from mechanical energy to electrical energy will be done by a generator, so the combustion engine has to convert the chemical energy of the fuel into mechanical (rotational) energy. The same procedure as with the electrical engines is done in order to find the best engine. A list of more than 30 combustion engines is made where for every engine the mass, maximum en continuous power is given. A plot of this list is made in Figure

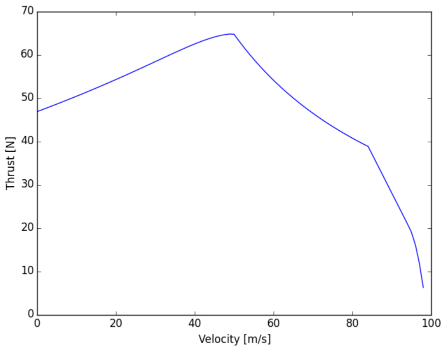


Figure 9.17: Thrust vs Velocity

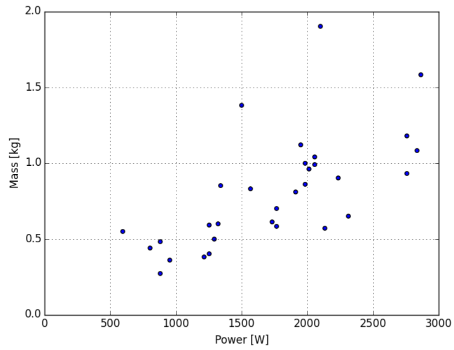


Figure 9.18: Combustion Engines

9.18 where the power versus mass is shown. Using this data, the best combustion engine for certain power requirements can be found. As no propeller is directly connected to the combustion engine, it can run at a constant and highly efficient speed, charging the battery and powering some systems from the generator. Therefore the maximum continuous power supply has to be found. The combustion engine is designed such that *Nora* can hover constantly at highest altitude until there is no fuel. This means that the continuous power needed is $2,000W$. The lightest engine that fulfils this requirement is the 95AX OS Engine which can produce $2,150W$. The engine weighs $0.57kg$ and has an efficiency of around 30% at $11,000RPM$. The combustion engine will need a starter as well, but because the engine is attached to a generator, this can function as a starter.

9.3.6 Generator

The mechanical (rotational) energy coming from the combustion engine has to be converted into electrical energy which can charge the accumulator and power all the electrical systems. This is done by the generator. An electric motor with a permanent magnet can be used as a generator, therefore the same brushless engines used for hovering and horizontal flight are considered. The maximum and continuous power requirements of the generator are the same as the combustion engine because they are directly attached to it. The combustion engine produces $2,150W$ at peak, so the electrical engine needs to be able to cope with that and covert it to electrical energy. The best generator is the same engine used for horizontal flight, namely the NTM Rotor Drive 600 Series which can generate up to $5,500W$ max and can generate up to $3,300W$ continuously. As the combustion will never reach those high power outputs, the generator is well within the requirements. The generator will weigh $0.34kg$.

9.3.7 Accumulator

During hovering or horizontal flight peak power situations may occur. Certainly during hovering, *Nora* is designed to be very manoeuvrable. In these situations the engines need more power than the combustion engine and the generator can produce. Therefore an accumulator is added, which can give an extra power burst to the system when needed. The sizing of the accumulator depends on several parameters. The accumulator needs to be able to operate at the correct voltage, in this case the required voltage is $22.2V$. This means that at least 6 lithium polymer cells are needed because one cell can provide $3.7V$. The cells are then placed in series such that $22.2V$ is reached. Another requirement is the amount of current that can be drawn from the accumulator. The peak current that will occur in the system is $165A$ which occurs when all hover engines work at full power. The generator can provide $75A$ during peak operation, meaning that $90A$ is needed from the accumulator during peak operation. The amount of energy stored in the accumulator should be able to let *Nora* hover for $2min$. The amount of energy calculated was $70Wh$. Now the best cell type has to be chosen. Similarly to the engines, a list of lithium polymer cells with their characteristics is made in order to find the most suitable accumulator for this application. The characteristics given are the capacity (Ah) and the max discharge (C) rate of the cell. Using Equation 9.48 the maximum current for each cell can be calculated. If this current is higher than the required $90A$ and there is enough energy, the cell can be used. The the lightest option is chosen. The chosen cell is the $LPHD533496$ which weighs $0.041kg$, so the total accumulator will weigh $0.25kg$, as six cells are needed.

The energy in the accumulator is $160Wh$, which is well within the requirement.[7]

$$A = C \cdot Ah \tag{9.48}$$

9.3.8 Fuel

The combustion engine needs fuel in order to generate energy. The amount of fuel is highly dependent on the type of mission. From simulations the amount of energy used during the complete mission is about $13MJ$. The efficiencies of all the electric engines, generator and propellers is already taken into account. Normal gasoline will be used because this gives a good efficiency for the combustion engine. The energy density of normal gasoline is $44.4MJ/kg$. If the combustion engine has an efficiency of about 30% and the generator and the electrical engines both have an efficiency of 90%, the fuel mass can be calculated using Equation 9.49 and is equal to $0.96kg$. The energy in the accumulator can be used as an extra, but the fuel is sized such that the energy of the accumulator is not needed in order to reach the endurance requirement. The density of gasoline is $0.77kg/L$, so the required fuel tank volume is $0.74L$.

$$m = \frac{13MJ}{44.4\frac{MJ}{kg} \cdot 0.3 \cdot 0.9 \cdot 0.9} \tag{9.49}$$

9.3.9 Heating & Cooling

The operating range of *Nora* is extremely high. It has to be able to operate from -40 to $+60°C$ air temperature, which puts high demands on all the different components, especially on the power and propulsion parts. To make sure that the components will still be able to operate, heating and cooling might be needed. In this section the heating and/or cooling for all the components is designed. Cooling can be calculated using the convective heat transfer formula which is given in Equation 9.50. In this equation the difference in temperature (ΔT), surface area (A) and the heat transfer coefficient (h). The heat transfer coefficient is assumed to be $250W/(m^2K)$, which is the coefficient between aluminium and air. If the required cooling power is known, the surface area for cooling can be calculated.

$$W = h \cdot A \cdot \Delta T \tag{9.50}$$

The electrical engines can operate at low temperatures but become less efficient at higher temperatures. The maximum allowed temperature for the electrical engines is $80°C$. At full power, the maximum heat produced by the electrical engines is $48W$. This is a direct result of the efficiency of the engine. In the most extreme case, where the air temperature is $60°C$, the required surface area should be $0.01m^2$. The area of the engine is $0.006m^2$, so extra 'ribbles' have to be added to increase the area which touches the air.

The generator produces more power and will therefore heat up more. The required cooling power is $103W$. Again using the same relations as before, the required surface area for cooling is $0.02m^2$. Because the generator is located inside the aircraft, a cooling link to the outside of the fuselage needs to be made. This link is made using a heat conductive material.

The combustion engine is the most inefficient engine and will produce the most heat. About $3,500W$ of heat is produced when the combustion engine is at peak power. The combustion engine can still operate at $100°C$ which means that the required cooling surface area should be around $0.35m^2$. An air gap will be made in the fuselage which can cool the engine and provide air for the combustion engine. In cold weather, the combustion engine will need to be heated before it can be turned on. The heating will be done electrically using resistors. The accumulator can then be used to heat up the engine.

The accumulator should not be cooled or heated for the temperature range *Nora* is flying. The fuel should be heated when the temperature is so low that the fuel is frozen. The fuel is then heated electrically using resistors. The power that can be drawn from the accumulator is $2,000W$ which is enough power to heat the fuel and the combustion engine in reasonable time.

[7] Accumulator Energy, URL `http://www.lipolbattery.com/high%20rate%20discharge%20lithium%20polymer%20battery.html` [Cited on 04/06]

9.3.10 Layout

The layout of the power and propulsion system can be seen in Figure 9.19. The figure is not drawn on scale. The Fuel is placed as close as possible to the center of gravity in order to minimise the effect of fuel consumption on the balance of the aircraft. The heaviest part, the combustion engine (IC) is placed close to the middle of the aircraft in order to keep the center of gravity there. The accumulator is split up into two packs of three cells as there is still space in the fuselage on both sides. The generator (Gen) has to be placed as close as possible behind the combustion engine to reduce the weight of the transmission in between the two parts. All the electric motors (DC) are connected to the propeller directly.

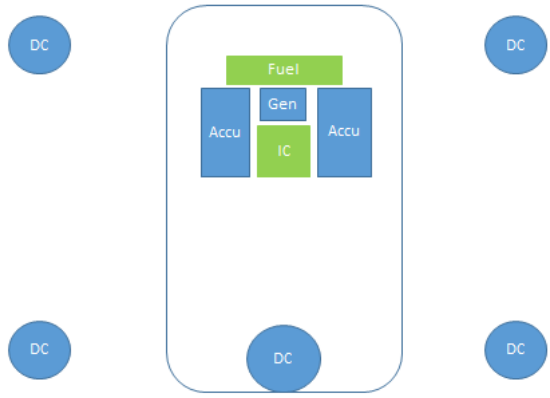


Figure 9.19: Power & Propulsion Layout

9.3.11 Results & Conclusion

Now everything of the power and propulsion has been sized. In Table 9.7 an overview of the selected components is shown. The total weight of the power and propulsion system (without cables) is $3.0kg$. The maximum continuous power that can be used is $2,200W$. The total price of the power and propulsion system is estimated to be €470.

Table 9.7: Power & Propulsion Overview

Part	**Specification**	**Weight** [kg]	**Amount**	**Power[W](Max)**	**Price €**
Thrust Propeller	Self Made	0.022	1	-	10.00
Thrust Engine	NTM Rotor Drive 600 Series	0.34	1	3300 (5500)	44.00
Combustion Engine	95AX OS Engine	0.57	1	2200	93.00
Hover Engine	NTM Rotor Drive 450 Series	0.096	4	950	16.00
Hover Propeller	Self Made	0.022	4	-	10.00
Generator	NTM Rotor Drive 600 Series	0.34	1	3300 (5500)	44.00
Accu Cell	LPHD533496	0.041	6	-	20.00
Fuel	Conventional Gasoline	0.96	1	-	0.53
Motor Controller	Red Brick 50A ESC	0.019	5	-	11.00
Total		**3.038**			**470.53**

9.3.12 Electrical Power Diagram

The way the power is divided over the whole system is shown in Figure 9.20. The power coming from the generator has a voltage of $44.4V$ which has to be converted to $22.2V$ before it can be used in the accumulator and the other engines. The accumulator can either be charged or discharged depending on the required power needed from the engines. Each engine has a controller which determines the actual current going to the engine. The same principle is used for the servos. Two servos are used for camera pointing system, five servos are used for the control surfaces and one motor is used for the zooming of the lens. The servos don't require a lot of power so these are connected to the accumulator directly. The servos require $6V$ so a voltage regulator between the accumulator and the servo is needed. All other components that need some power are connected to the USB bus. This is done because the different components need different voltages and the USB bus is able to accommodate for all these differences. USB 3.1 is able to have 4 different voltages on the bus.

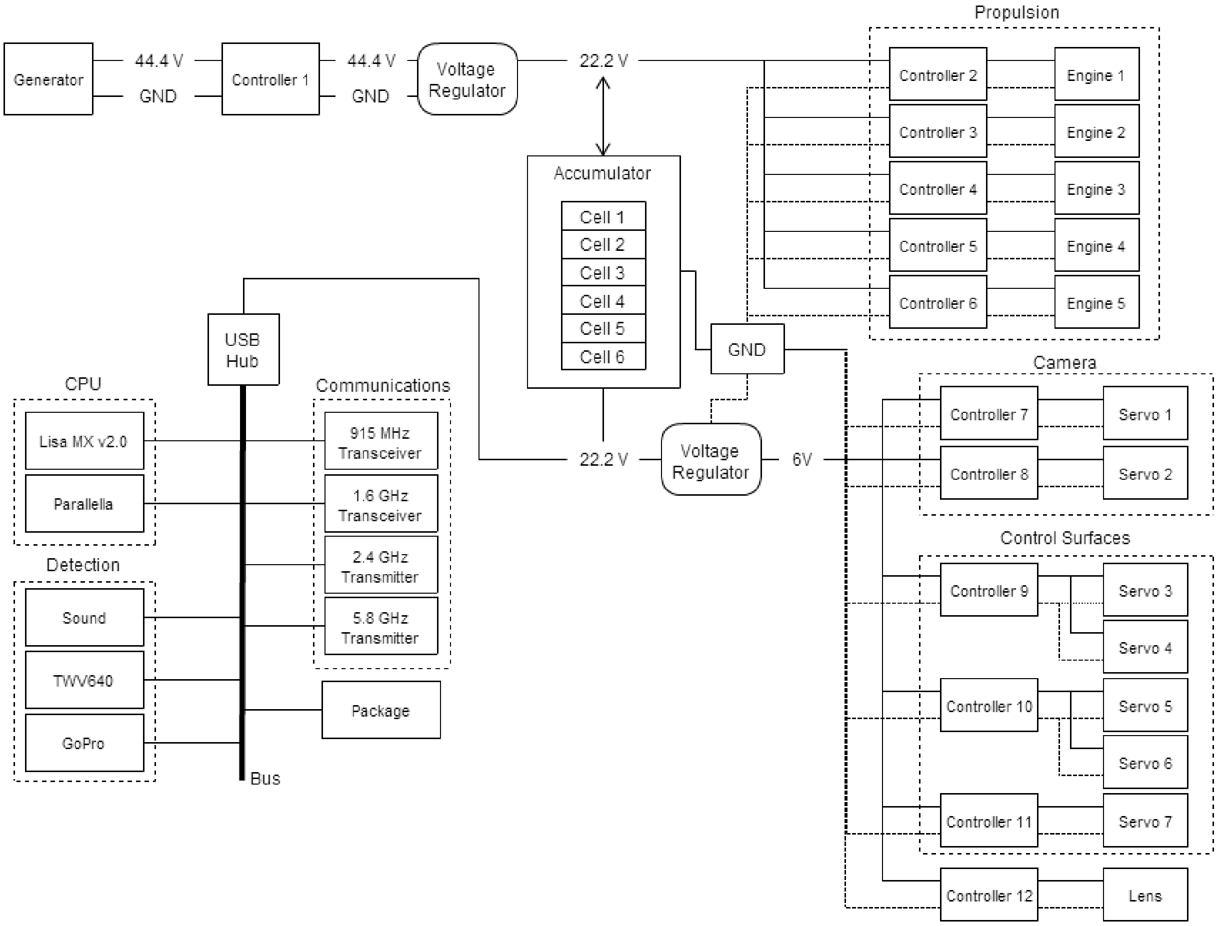


Figure 9.20: Electrical Power Diagram

9.4 Stability

The stability of *Nora* has high implications on the control system. The stability can be divided into two categories, namely hover stability and longitudinal stability.

9.4.1 Hover

It can be very easily shown that quadcopters are inherently unstable. Imagine a quadcopter in horizontal hovering equilibrium position. While no external forces and moments are applied, the system will obviously remain in its equilibrium. However if the equilibrium would be broken for example by an increase in the roll angle, there is no automatic reaction to the forces on the device. This means that the thrust vector remains at this roll angle and *Nora* will start drifting out of its position. Thus showing that the quadcopter is unstable. The same can also be shown by analyzing the more elaborate non-linear quadcopter dynamics or by doing a Jacobian linearization, but this is not necessary due to the fact that *Nora* will be autonomous and will therefore need a controller regardless.

It is however interesting to analyse the allowable center of gravity range in order for *Nora* to be controllable. This should be done for both the longitudinal as the lateral center of gravity position. Setting the thrust of the two front engines to 90% of the maximum thrust (reserving 10% for manoeuvres) allows us to determine the thrust required by the rear engines to remain in the air. The sum of moments can then be taken around any arbitrary point (the front of the vehicle was chosen for simplicity). Since the sum of moments should be zero, the only variable that remains in the equation is the center of gravity for which the equation can be solved. This center of gravity is evidently the most forward center of gravity that is allowed. The same can be done for the rear center of gravity by setting the thrust of the rear engines to 90% of the maximum. The analysis for the lateral centers of gravity is exactly the same as that of the longitudinal center of gravity and therefore it will not be discussed. The result of both analyses is shown in Figure 9.21. It can be seen that the allowable centers of gravity are dependent on the altitude which can be expected since the available thrust changes with the air density. At $5000m$ the most forward center of gravity that is still controllable is $56cm$ when measured from the tip. Additionally it can be seen that the lateral allowances are outside of the body, so they should be easily achievable.

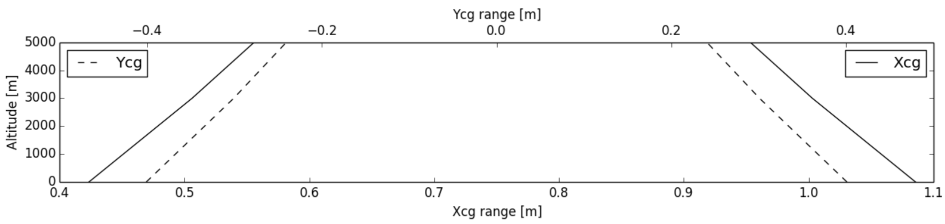


Figure 9.21: Allowable Center of Gravity Ranges at Different Altitudes

9.4.2 Longitudinal Stability

Essential in horizontal flight is the longitudinal stability of the aircraft. Although an aircraft can be made artificially stable with an active flight controller, it is preferable to have the aircraft correct itself for disturbances. This is of additional importance given the small size of *Nora* and the gusty environment she has to operate in. Therefore, longitudinal stability was considered one of the top level design requirements in planform design, as outlined in Subsection 9.2.1.

Longitudinal stability is limited by the neutral point. When the center of gravity coincides with the neutral point, the aircraft is insensitive to any disturbances. With the CG moving forward, the aircraft becomes increasingly stable. By moving the CG in XLFR5, the neutral point is found experimentally to lie at $0.66m$ as measured from the nose of *Nora*. Hence, *Nora* will be stable with the center of gravity anywhere in front of $0.66m$. This neutral point was found to be unaffected by an altitude change. Combining this with the controllability covered in the previous subsection, the control-stability interval ranges is established to range from $0.55m$ up to $0.66m$ at high altitude and $0.42m$ up to $0.66m$ at sea level.

It is important to note about these ranges that the front limit is a hard limit in controllability. Moving the center of gravity more forward would mean *Nora* is uncontrollable in hover flight. For cruise flight this forward limit has no implications. The aft limit is less crucial. Having the CG move behind the neutral point of $0.66m$ means *Nora* becomes statically unstable. She then needs to be actively controlled in order to maintain heading and altitude. The controller is tested for this situation and capable of keeping *Nora* stable. However, it is suboptimal compared to inherent stability, especially in particularly gusty weather.

9.5 Control

This section will describe the controller that was designed to provide artificial stability to *Nora*. First the control types that were considered will be given. Then the layout of the hover controller will be given. Next the cruise controller and the transition controller will be discussed. After that the hardware of the controller will be elaborated upon. Finally some recommendations will be given for the future developments of the controller.

9.5.1 Control Types

A controller is required to provide the required autonomous flight capabilities. This subsection discusses the different control techniques that were considered. It will also discuss which control technique was selected.

With the rise of computer technology, control theory has seen some big jumps forward. The result is that there are now multiple available control techniques to stabilise systems and force convergence. The most interesting techniques that were considered are a state-space control system, a Proportional Integral Derivative (PID) controller and a model predictive controller.

A model predictive controller was the first one to be deemed unfeasible. The main reason for this is that they are designed specifically for process industries such as chemical plants and oil refineries. In resent years vehicle path planning and control has emerged as one of the alternative applications of model predictive controllers [35]. However there is little information available about this application and that combined with the relative lack of knowledge about model predictive controllers resulted in it being deemed unfeasible.

State-space descriptions describe the dynamics of a system as a set of coupled first-order differential equations. In these equations there are certain input variables called state variables which are coupled with output variables through algebraic equations. State space models reduce limitations when compared to classical control theories by implementing a 'richer' description of the system dynamics [36]. The problem that is encountered with state space representations is then logically that also a 'richer' knowledge of the system dynamics is required. In theory this problem is relatively small since a lot of research has been done into aircraft dynamics, however in practise the design to be controlled is of an unconventional nature. This means that a lot of research has to be done into the dynamics of this specific design, which due to time and resource constraints is not feasible for the controller. Therefore the state space controller was discarded as an option.

This leaves us with a PID controller. This type of controller analyses the proportional, integral and differential part of the error combined with tunable gains to determine the required outputs of the system. A PID controller is categorised as the best controller in the absence of knowledge of the process to be controlled [37]. It is relatively simple in its application when compared to the other control techniques. Additionally PID controllers have been proven to work for small scale UAV autopilots [38]. For these combined reasons a PID controller was selected as the best solution for the controller.

9.5.2 PID Controls

A PID controller works by analysing the error of a system with respect to its intended position. This error is analysed in three ways which will all be explained in this subsection.

First of all the error is analysed proportionally. This is indicated by the P. The formula used to analyse the error proportionally is shown in Equation 9.51. Here K_P indicates the gain by which the error is multiplied to give the output. Overall the proportional analysis corrects for errors in a simple way, but when used alone it shows a tendency to result in oscillatory behaviour. Additionally it does not compensate for external influences such as wind (the system may be stable outside of its reference position).

$$u(t) = K_P e \tag{9.51}$$

The latter of the two mentioned defects can be solved by using an integral analysis. This analysis is indicated by the I and is shown in Equation 9.52. Once again K_I indicates a gain by which the integral over the error is multiplied to result in the intended effect on the output and i indicates the current index. It is imported to notice that the controller should work on discrete time series instead of a continuous time series. This means that the integral is increased by finite amounts at every time step. As mentioned before the integral analysis can help by compensating for external effects such as winds.

$$u(t) = K_I \sum_{0}^{i} e_i \Delta t \tag{9.52}$$

Finally a differential analysis was added to remove the oscillatory effects that were mentioned before. The differential of the error is denoted by the D and its formula is shown in equation 9.53. Here K_D once again denotes the gain by which it is multiplied and i denotes the current index. The differential analyses also has to cope with the discrete time series, but it is solved in a way similar to that of the integral analysis. This analysis reduces oscillations and helps to convergence to the desired reference equilibrium.

$$u(t) = K_D \frac{e_i - e_{i-1}}{\Delta t} \tag{9.53}$$

9.5.3 Hover Controller

The hover controller consists of two consecutive PID-loops to determine the four different thruster settings. The layout of the controller is displayed in Figure 9.22. The first PID loop as indicated by the (1) analyses the position errors in a Cartesian coordinate system. The z-position error (altitude) is directly used as an output that determines a thrust delta for climbing or descending. The x- and y-position errors are used to determine the required roll and pitch angles. These are then once again combined with the sensors to find the respective errors of the angles to be analysed in the second part of the PID controller indicated by the (2). This will then result in extra thrust differences to control these angles which completes the feedback loop.

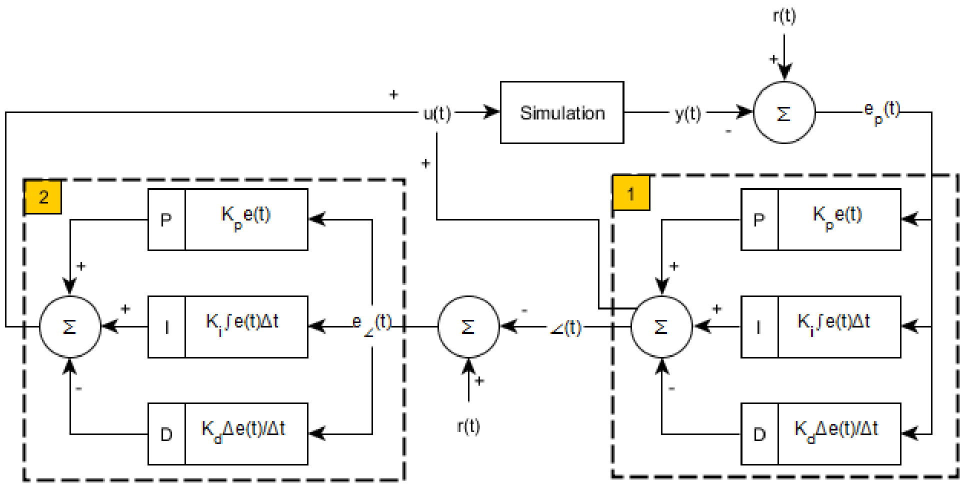


Figure 9.22: Hover Controller Schematic

9.5.4 Cruise Controller

The cruise controller is significantly more complicated then the hover controller. A detailed structure of the controller is shown in Figure 9.23. The initial PID loop as indicated by the (1) analyses the error of the heading. This PID loop determines the required roll angle to compensate for the error. This intended roll angle also feeds into the target pitch angle which will be discussed later. The loop indicated by the (2) analyses the errors of the altitude. This loop directly feeds the forward thruster as an output, but it also adds to the target pitch angle just like loop (1). PID loop (3) is the last and main driver for the target pitch angle. Loop (3) analyses the error of the velocity. The error in the roll angle is evaluated in loop (4). This loop is used to directly control the ailerons. Finally loop (5) analyses the error in the pitch angle and the result determines the elevator setting which completes the feedback loop.

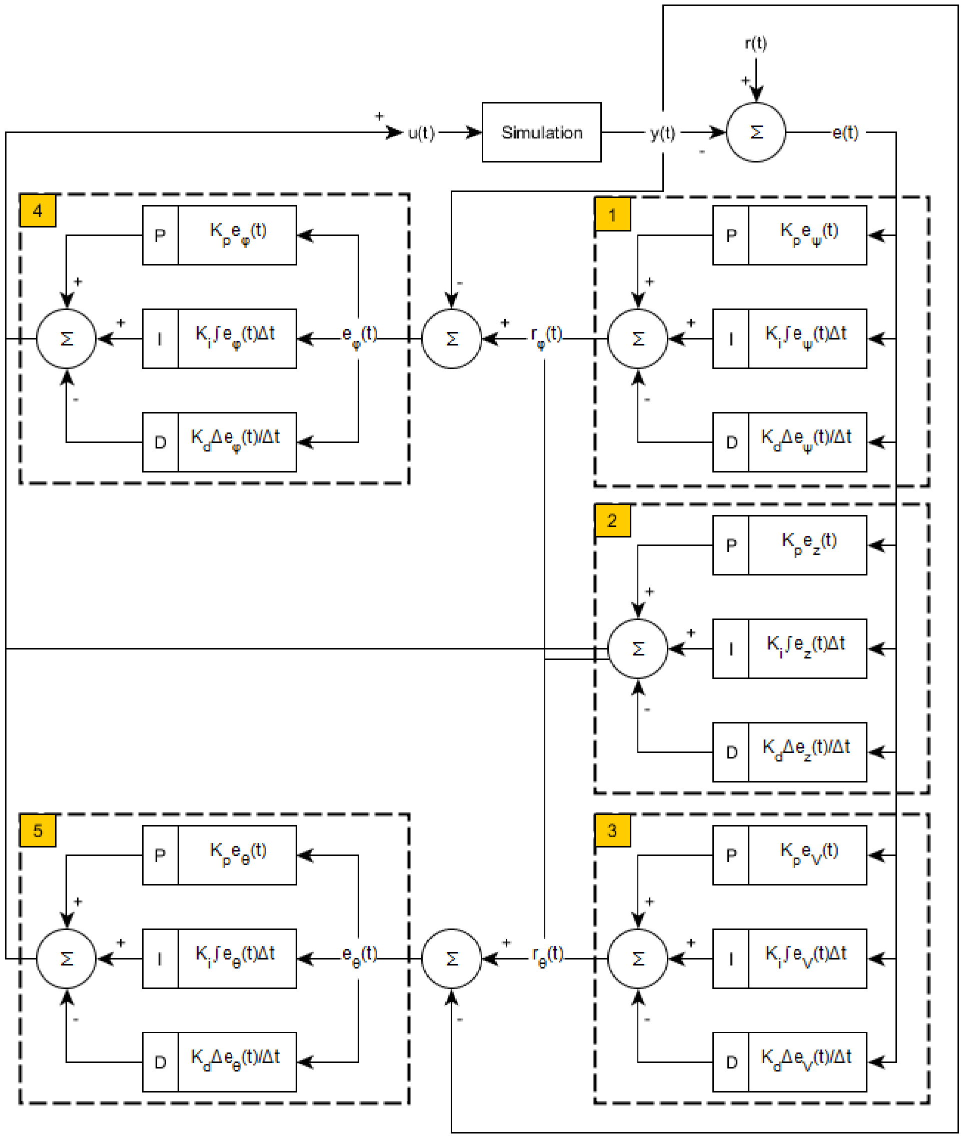


Figure 9.23: Cruise Controller Schematic

9.5.5 Transition Controller

The transition controller is the control system that regulates the transition between hover and flight mode and vice versa. It is an adaption of both the other controllers. It combines loops (1) and (2) from the hover controller and loops (4) and (5) from the cruise controller. This means that yaw is controlled by the hover controller, while the target roll angle is set to 0. This roll angle is concurrently controlled by both the hover controller and the cruise controller. The target pitch angle is set to 1.4°, which is the design angle of attack for cruise. This pitch angle is also controlled by both the hover and the cruise controller simultaneously. Finally altitude is controlled solely by the hover controller, while the forward thruster is set to near full thrust. This results in a fast and stable transition between hover and cruise. For the transition between cruise and hover a different and more simplistic solution was chosen. To provide this transition the cruise controller can simply be turned of and the hover controller turned on. This combined with a target in the distance resulted in a stable transition.

9.5.6 Sensor Merging

Because multiple sensors can be used to determine the same state of the system, the system is in need of a system to merge all the information to obtain the best possible result. Therefore an unscented Kalman filter will be used. With the Kalman filter, all the measured data will be combined to obtain a single value for each degree of freedom in the system. It makes use of the known variance of each sensor, which is described in the datasheet of the sensor or obtained by testing the sensors before implementation. Eventually all the degrees of freedom of the system, such as the position of the vehicle, are determined with an improved accuracy over the data acquired by using a single sensor. Since the variance of each sensor is known, the accuracy can also be determined. The unscented variant of the Kalman filter, will be used to account for nonlinear motions and improve the results. [39]

9.5.7 Controller Hardware

The following section describes the proposed hardware and operating system used in *Nora*. To accommodate for a system that is capable of the above described functions, the picked hardware is listed in Table 9.8. For the main flight controller, or auto pilot, the Lisa/MX is chosen. This is mainly due to the large amount of servo ports, necessary to control all engines and servos during flight operations. And a high computational performance with a high clock speed, compared to the other Paparazzi flight controller boards. The flight controller runs Paparazzi, a free open-source software package, software that includes a PID controller and a Kalman filter to analyse all the data. The primary sensors, the on-board inertial measurement unit (IMU), provides *Nora* with an accelerometer (3-axes), a gyroscope (3-axes), a magnetometer (3-axes) and barometer (1-axis). In combination with the GPS receiver, the system can determine its position. For redundancy, a second IMU is implemented, being able to control the aircraft when the primary IMU fails. For landing and take off, an estimation of the ground effect is necessary, therefore two sonic sensors are implemented in the main wing, to achieve high accuracy (*mm*-resolution) height measurements. The pitot tube is essential due to the high wind and gust conditions during operations. It allows the flight controller to determine the airspeed in flight direction. The light sensor allows for the control of the aircraft lighting system, where the humidity sensor will be used for internal temperature conditioning systems.

Table 9.8: Component Budget Breakdown

Part	**Specification**	**Price [€]**	**Mass [kg]**	**Power [W]**
Navigation & Control PE	Lisa/MX v2.0 with 10DoM Aspirin IMU by Transition Robotics	200	0.011	1.25 (max 2.9)
Sensors IMU	ADAFRUIT 10-DOF IMU BREAKOUT - L3GD20H + LSM303 + BMP180	26	0.0028	unknown
GPS receiver	ADAFRUIT ULTIMATE GPS BREAKOUT - 66 CHANNEL W/10 HZ UPDATES	35	0.0085	0.14
Sonic Sensor (2x)	MAXBOTIX ULTRASONIC RANGEFINDER - LV-EZ4	22	0.0042	unknown
Humidity Temp sensor	DHT22 TEMPERATURE-HUMIDITY SENSOR + EXTRAS	8.70	unknown	0.0125
Light Sensor	ADAFRUIT TSL2591 HIGH DYNAMIC RANGE DIGITAL LIGHT SENSOR	6.10	0.0011	unknown
Pitot Tube	Airspeed Sensor Kit	21.89	0.0040	unknown
Total		**319.8**	**0.03143**	**1.4**

9.6 Structures & Materials

This Section introduces the overall structural design methodology and material selection process. It commences with a brief overview of used theories and equations after which the section continues onwards with a more detailed analysis of major individual components such as the main wing and fuselage designs. Concomitantly, the section touches upon the material choice for each subsystem and presents the relevant rationales. It then continues with completed verification strategies for the presented results. Vibrational characteristics of the structural components are analyzed and presented and details regarding the separability and connectivity of *Nora* are given. Lastly in Subsection 9.6.12 a production plan of both the UAV and the package is elaborated upon. Fiannly, please refer to Section 10.7 for the fatigue characteristics of the individual components.

9.6.1 Structural Analysis Fundamentals & Design Approach

This Subsection will succinctly provide insight into the structural analysis fundamentals that have been used in determining optimal structures and will furthermore give some information on the general design approach which has been conducted fully in Python algorithms. Please refer to Figure 9.27 for an outline of the general structure of the structural analysis codes.

Loading Diagrams
The aircraft structural design is centered around the maximum expected loading including both maneuvering and gust factors; please refer to Figure 9.24 for the relevant graphs. Loading factors in this Figure were subsequently increased by an additional 50%, as is custom according to *European Aviation Safety Agency* [40], to obtain the ultimate loading acceleration (ULF) which the structure should cope with under all circumstances. As is clear from Figure 9.24, the gust loads were determined critical for the designed UAV and were based on gust peaks presented in the *Midterm Report*.[3] Maneuvering maximum loads were taken from *European Aviation Safety Agency*[40], and represent the g-load experienced during a minimum radius turn at cruise velocity.

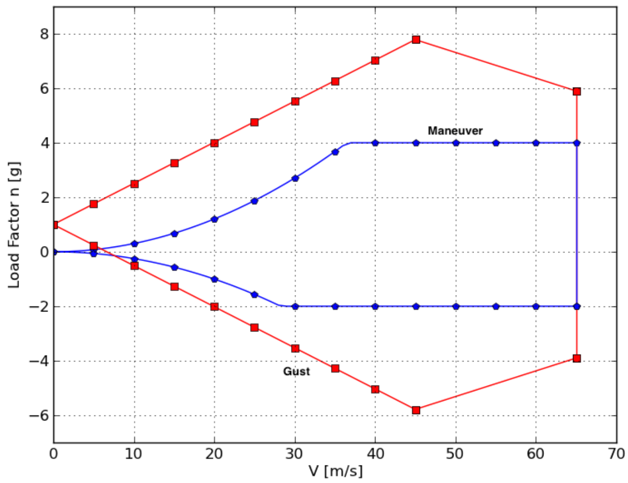


Figure 9.24: Maximum Loading Factors

Reference Frame
For the entire structural analysis, a right-handed *Body Fixed* reference frame was used, whereby *Nora*'s center of mass was used as the origin; please refer to Figure 9.25. This reference frame exhibits the characteristic X_b-axis in the symmetry plane of the aircraft pointing toward the nose. The Z_b-axis also lies in the symmetry plane and points in *Zenith* direction. Finally, the Y_b-axis lies perpendicular to the symmetry plane and points outward to the left.

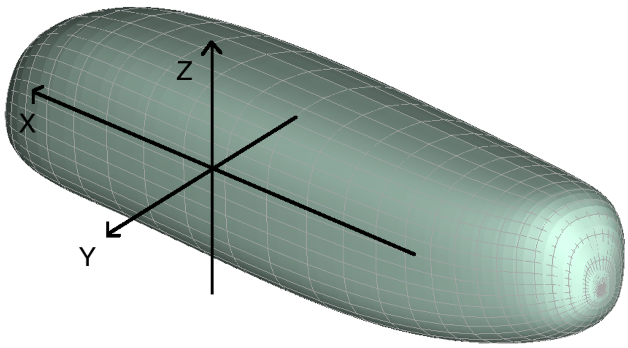


Figure 9.25: Structural Body Fixed Reference Frame

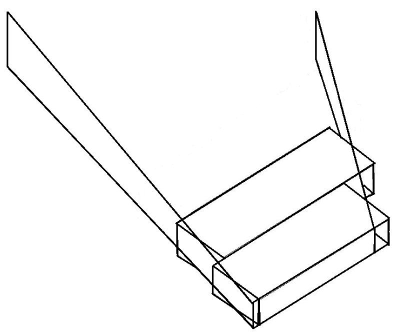


Figure 9.26: Structural Discretisation

Force Analysis
With the found loading diagrams as mentioned, the ultimate loads on the structure were determined. For this, each individual component, such as the vertical stabiliser or canard, was discretized in n subsections for which the geometrical characteristics such as the centroid and moments of inertia, on a per part basis, were assumed constant; please refer to Figure 9.26 for an overview of the used discretization approach. The three dimensional structural analysis of each part included three forces in all axis directions resulting in both shear and compression or tension. As referred to, the forces were post facto multiplied by the ultimate loading factor as the example of Newton's Second Law in Equation 9.54. Relevant forces for all subsections include lift, drag, horizontal flight thrust, vertical flight thrust and gravity.

$$F_{ULF} = m \cdot a \cdot ULF \tag{9.54}$$

$$M_{x_b} = F_{n_{z_{ULF}}} \cdot x_n \tag{9.55}$$

Moment Analysis
Each of the three orthogonal forces analysed component wise per definition created at least one moment about the relevant axis to which it applies. As an example, given the lift force of the main wing lies aft of *Nora*'s center of mass, the lift creates both a moment around the X_b and Y_b axes, see Figure 9.25. According to moment theory, as presented in Equation 9.55, the moment around X_b would for instance include influences of both the force and arm. Relevant moments include both bending moments around all axes as well as torsional moments around certain axes.

Stress Analysis
After all forces and moments were found per discretized element for each structural subsection such as the fuselage or landing gears, stress calculations ensued. Unsymmetrical bending theory was used for the determination of the bending stresses as outlined in Equation 9.56 for a bending stress around the Z_b-axis.

$$\sigma_z = E_{z_i} \left[\left(\frac{M_y I_{xx} - M_x I_{xy}}{I_{xx} I_{yy} - I_{xy}^2} \right) x + \left(\frac{M_x I_{yy} - M_y I_{xy}}{I_{xx} I_{yy} - I_{xy}^2} \right) y \right] \tag{9.56}$$

Note that in Equation 9.56, composite theory has been applied in accordance with the moment of inertia calculations as detailed in Equation 9.57. In both these equations, the subscript i relates the different materials used.

$$I_{xx} = \int_A E_{Z_i} Y^2 dA \tag{9.57}$$

Once the bending stresses had been computed per discretized element for each structure, the shear stresses were analyzed using both torsion theory as well as shear theory. Both theorems produced together the shear flows present in the entire structure at discretized locations. The basic shear flow was found using Equation 9.58.

$$q_b = -E_{Z_i} \left[\left(\frac{F_x I_{xx} - F_y I_{xy}}{I_{xx} I_{yy} - I_{xy}^2} \right) \int_0^s t_i x ds + \left(\frac{F_y I_{yy} - F_x I_{xy}}{I_{xx} I_{yy} - I_{xy}^2} \right) \int_0^s t_i y ds \right] \tag{9.58}$$

The closed section shear flow, in turn, was found using Equation 9.59, where p is the force arm and A is the sectional enclosed area. Torsion theory was used to supplement the found shear flows in Equations 9.58 and 9.59 as outlined in Equation 9.60.

$$q_{s_0} = -\frac{\oint p q_b ds}{2A} \tag{9.59}$$

$$q_T = \frac{T}{2A} \tag{9.60}$$

Finally, the elemental total shear flow was the summation of all three shear flow components, taking into account potential relieving effects such as counteracting flows. This is outlined in Equation 9.61. The shear stress per element per structural component is then simply the pertinent local shear flow q divided by the local thickness t, as shown in Equation 9.62.

$$q = q_b \pm q_{s_0} \pm q_T \qquad (9.61) \qquad\qquad \tau = \frac{q}{t} \qquad (9.62)$$

Stress Concatenation
Once the bending and shear stresses were found per element, both had to be concatenated according to the Von Mises stress theorem in order to be of any use in structural optimisation and material selection, see Equation 9.63. The resulting stress was then used for further analysis regarding material yielding and minimum structural dimensions for non-failure.

$$\sigma_v = \sqrt{\sigma^2 + 3\tau^2} \qquad (9.63)$$

Buckling
Each structural component has also been checked for buckling according to Euler's buckling theory. This theorem was used as an additional safety for structural integrity, and was controlled for every discretization alone assuming pinned connections (pinned was chosen as additional safety since most sections are fixed at both ends). Please refer to Equation 9.64 for the buckling criterion used. Also note that l refers to the discretized section length and R is the radius of gyration of that element.

$$\sigma_{cr} = \frac{\pi^2 E_{Z_i}}{(l/R)^2} \qquad (9.64)$$

Castigliano's Second Theorem
In addition to verifying whether the structural components do not buckle under the loading conditions, a Castigliano analysis was undertaken on all five wings as a control on the maximum tip deflections. These tip deflections are heavily dependent on both the loading as well as the structural bending stiffness. For this analysis, Castigliano's Second Theorem has been used as outlined by Equation 9.65. Tip deflections were structurally minimized to avoid loss of lift, material fatigue as well as reduce the vibrational harm to the system, see 9.6.10.

$$C_i = \int_0^L \frac{M^2}{2EI} dz \qquad\qquad \Delta = \frac{\delta C_i}{\delta M} \qquad (9.65)$$

General Approach
Given the frequently used structural analysis theory presented above, the general approach to the design has been relatively straightforward and repetitive. The enumeration below will provide some information on the structural design process as well as the ordering of steps taken.

1. **Component Discretization:** Each structural component (e.g. main wing, canard, fuselage) has been discretized in at least 20 elements for which the geometrical characteristics are deemed constant. More discretization leads to better result accuracy.
2. **Element Characteristics Determination:** Determination of structural characteristics concerning centroids and moments of inertia.
3. **Force Introduction:** Forces in all three dimensions are introduced per discretization.
4. **Moment Resultant:** Moments and torques in all three dimensions are deduced from the forces present per element and the distance between the location on that element and the rotation axis.
5. **Stress Computation:** Shear and normal stresses are calculated based on the forces, moments and torques present. The separate stresses are concatenated per element.
6. **Thickness Reduction:** Based on maximum allowable dimensions of the structure (e.g. fuselage radii or airfoil and chord shape), the thickness is iteratively reduced until material yield occurs.
7. **Additional Checks:** Prior to finalizing the thickness distribution, additional checks are performed on the structure such as cut out analysis on the fuselage, buckling and deflection analysis as well as vibrational flutter checks.
8. **Mass and Cost Estimation:** If all checks prove satisfactory, the mass and cost are estimated per component as well as in total for the entire structure.

Please refer to Figure 9.27 for a high-level structural code flowchart.

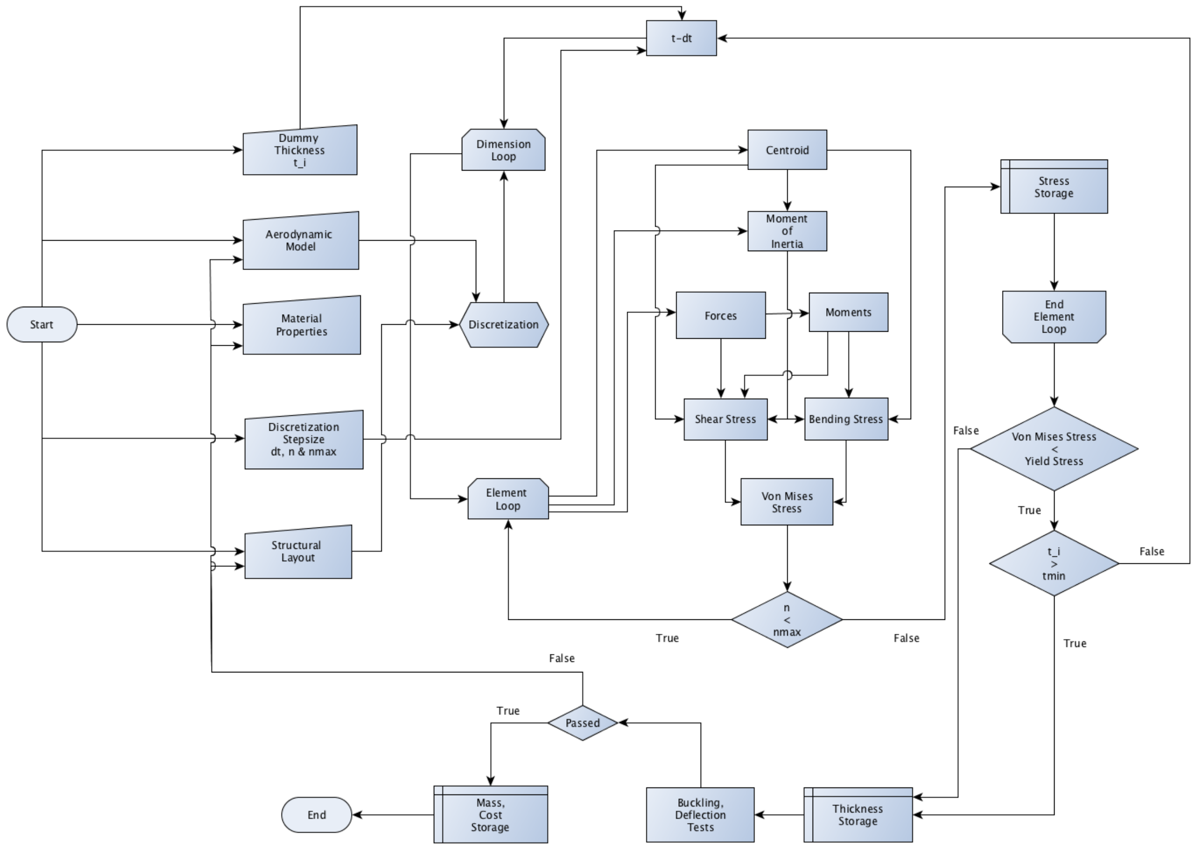


Figure 9.27: Structural Analysis Code Flowchart

9.6.2 Materials

Before commencing with the structural design of *Nora*, a rationale on the material choice is in place. In the mass budget, $4.1kg$ of the total design mass of $11kg$ was initially allocated to the structural design, see Section 6.6.4. This ratio is in line with *Synthesis of Subsonic Airplane Design* [28], but is a relatively small considering the size that is being designed for as well as the complexity and number of fuselage appendages. High priority is thus given to keeping the mass as low as possible due to its inherent importance for the mission operations. Increasing the mass would jeopardize the system's capability of flying with the limited wing span of $1.5m$ or else would reduce the amount of payload or sensors that could be taken on board. Therefore, high-end lightweight materials in sandwich structures are chosen to maximize structural characteristics with minimum mass. Examples of such materials are carbon fiber reinforced Nylon-12 polymers (CFRP), Airex C70-40 structural foam and Acrylonitrile Butadiene Styrene (ABS) plastic. Furthermore, the wing mounts that carry most loads are constructed from Ti-6Al titanium to minimize weight for maximum yield stress and stiffness characteristics. All the characteristics per material can be found in Table 9.9. To get these characteristics, a penalty must be paid in the manufacturing cost. The lower the manufacturing factor, the higher the manufacturing cost. Material choice and cost analysis have been validated by Jos Sinke, head of the *Aerospace Materials & Structures Laboratory* at TU Delft.

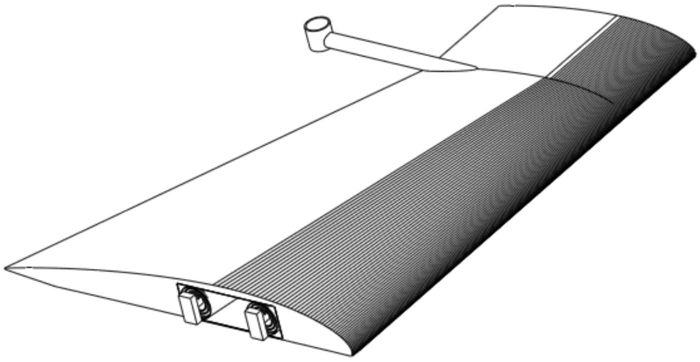
9.6.3 Main Wing Structural Design & Material Selection

The structural characteristics that were used in the design process of the main wing are detailed in Table 9.10 and were obtained from the aerodynamics design as presented in Section 9.2. For the internal structure, it was decided to investigate two types of layout, namely a tubular spar and a square wing box located roughly at the quarter chord location. Also, a combination of both a square and tubular wing box was analysed, which proved capable to sustain the loads at a lower design thickness as expected. These internal thin-walled structures were each designed to fully carry all loads including the ultimate loading factor. For the main wing, the optimal solution taking both mass and cost into account equated

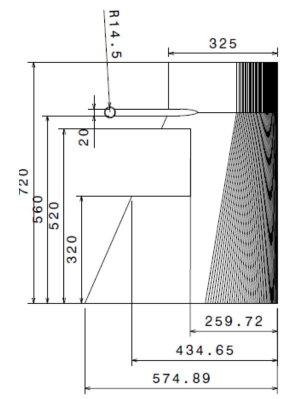
Table 9.9: Material Characteristics

	Density [kg/m^3]	Tensile Yield Stress [MPa]	Young's Modulus [MPa]	Material Cost [€]	Manuf. Factor [-]
6061T6	2700	275	69000	10 / kg	0.4
PA640 GSL	840	49	85000	170 / kg	0.1 - 0.2
ABS	1040	35	2800	12 / kg	0.5
EPS	25	0.2	2	6 / kg	0.8
Airex C70-40	40	0.45	28	9.2 / kg	0.8
Ultracote	1100	-	-	1.2 / m^2	0.8
Ti-6Al	4430	880	113800	50 / kg	0.2
Airex C70-200	200	5.2	175	16 / kg	0.8

to the combined thin-walled structure using both a tube and a rectangular wing box, see Figure 9.28 for the main wing structural layout. See furthermore Figure 9.29 for the internal loadings of the main wing with span location and Figure 9.30 for a 3D plot of the Von Mises stress. A technical drawing of the main wing assembly can be found in Figure 9.28. Foam was implemented as the fill material for the main wing, fully determining the airfoil shape and was furthermore primarily tasked with buckling avoidance of the thin-walled internal structure by passive compressive bending load subjection. The entire structure was sized to the maximum acceptable dimensions according to the size factors presented in Table 9.10. As such, given the wing is tapered, the internal structure is tapered as well towards the tip. The total airfoil cross sectional area excluding thin-walled circumscribed areas was filled with foam.



(a) Isometric View



(b) Main Wing Top View

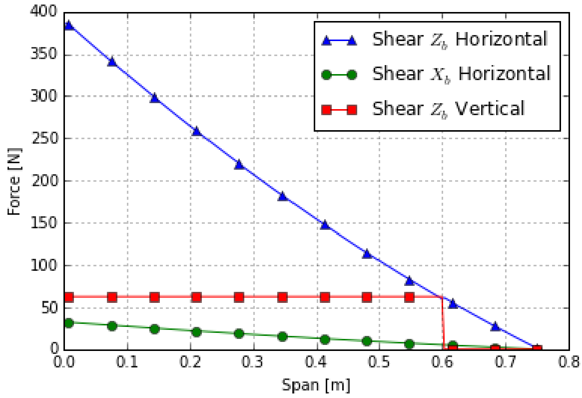
Figure 9.28: Main Wing Assembly

Iterations over the required thickness for the constraint of structural yield at material yield resulted in the required mass and concomitant cost of the main wing. The thin-walled structure was analysed for 6061T6 aluminum, PA640 GSL isotropic carbon fibre as well as Acrylonitrile Butadiene Styrene (ABS) plastic. For the foam, both the widely applicable Expanded Polystyrene (EPS) as well as the construction foam Airex C70-40 were analysed. Finally, to protect the external foam planform, an additional weather-proof coating was taken into account in the mass and cost calculations which has no load bearing responsibilities. For this purpose, a thin layer of Ultracote was used such as prevalent in this category of UAV aircraft. In general, aluminium and ABS plastic were found not feasible since their density is simply too large for *Nora*'s size and loading while EPS foam has too weak strength characteristics and would buckle under the compressive bending load.

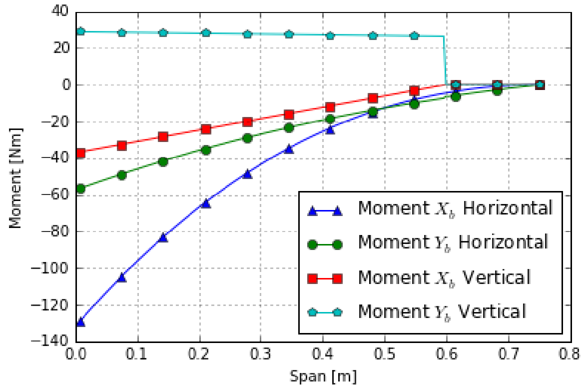
Please refer to Table 9.11 for the estimated mass and cost of the optimal structure.

9.6.4 Canard Structural Design & Material Selection

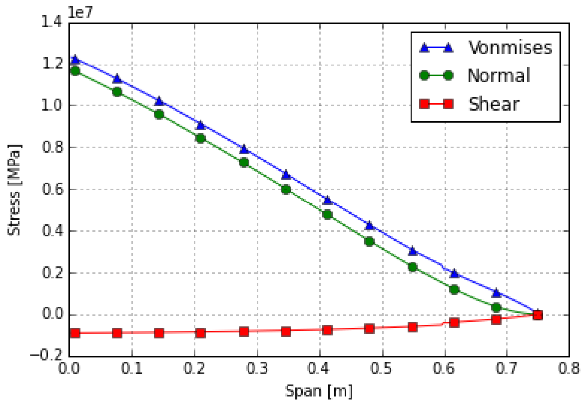
The structural characteristics that were used in the design process of the canard are detailed in Table 9.13 and were obtained from the aerodynamics design as presented in Section 9.2. As for the main wing, two internal structures were investigated, and similarly, the canard structural performance characteristics



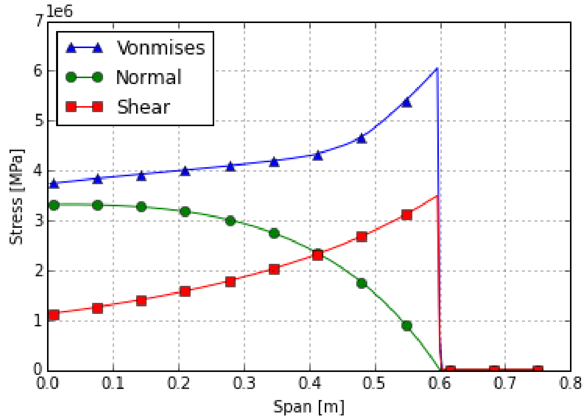
(a) Force Distribution



(b) Moment Distribution



(c) Stress Distribution - Horizontal Flight



(d) Stress Distribution - Vertical Flight

Figure 9.29: Load Distributions over Main Wing

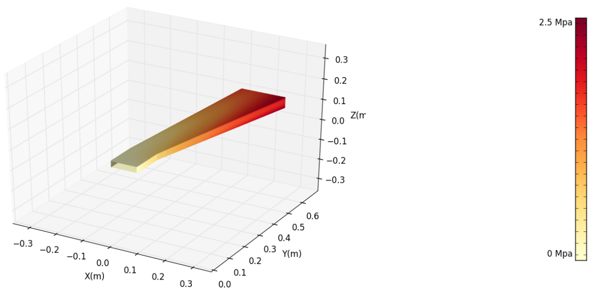


Figure 9.30: Von Mises Stress on Main Wingbox

Table 9.10: Main Wing Characteristics

Parameter	Value	Unit	Parameter	Value	Unit	Parameter	Value	Unit
Root chord	0.58	m	Lift/Drag	12	-	Half wing span	0.75	m
Tip chord	0.33	m	Sweep	0	°	Engine location	0.15	m
ULF	12	-	Engine mass	0.3	kg	t/c	0.15	-
Lift	32	N	Engine thrust	65	N	Engine strut l.	0.35	m
Wing box w.	40	%c	Wing box h.	10	%c	Wing box rad.	5.0	%c

were optimized by the combined tubular spar and a square wing box located at the quarter chord. See Figure 9.31.

Additionally, foam was implemented as the fill material for the canard determining the airfoil shape and tasked with buckling avoidance of the thin-walled internal structure. The entire structure was sized

Table 9.11: Mass & Cost Estimate per Main Wing

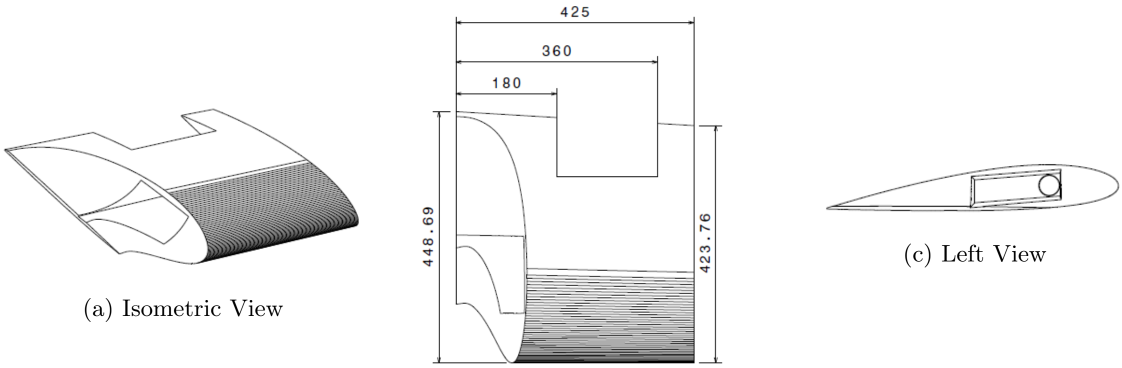
Structure Type	Mass [kg]	Cost [€]
Combined Square & Tubular	0.45	210.00
Structure Material		
Carbon		
Foam Material		
Airex		

Table 9.12: Main Wing Structure

Material	Thickness [mm]
CFRP	0.4
Foam	15

to the maximum acceptable dimensions according to the size factors presented in Table 9.13. This meant the internal structure is tapered towards the tip. The total airfoil cross sectional area excluding thin-walled circumscribed areas was filled for 50% with foam here too.

Material selection was based on the same options as for the main wing as also described in 9.6.2 and produced the same output with regards to material selection as outlined in 9.6.3. Please refer to Figures 9.32 and 9.33 for the relevant force, moment and Von Mises distributions over the wing span.



(a) Isometric View

(b) Top View

(c) Left View

Figure 9.31: Canard Geometry

Table 9.13: Canard Characteristics

Parameter	Value	Unit	Parameter	Value	Unit	Parameter	Value	Unit
Root chord	0.45	m	Lift/Drag	12	-	1/2 wing span	0.43	m
Tip chord	0.42	m	Sweep	0	°	Engine loc.	0.60	m
ULF	12		Engine mass	0.3	kg	t/c	0.15	-
Lift	22	N	Eng. thrust	65	N	Eng. strut l.	0.15	m
Wing box w.	40	%c	Wing box h.	10	%c	Wing box rad.	5	%c

Table 9.14: Mass & Cost Canard Estimate per Canard

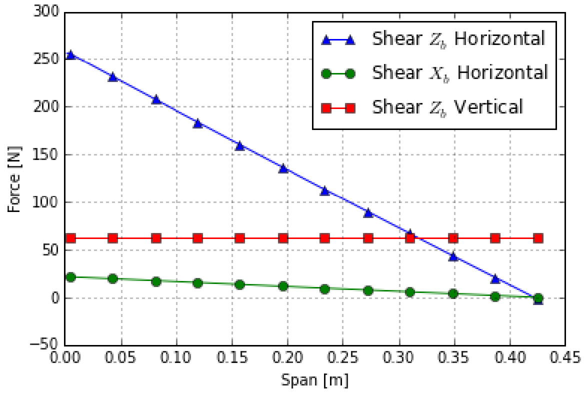
Structure Type	Mass [kg]	Cost [€]
Tubular	0.26	55
Structure Material		
Carbon		
Foam Material		
Airex		

Table 9.15: Canard Structure

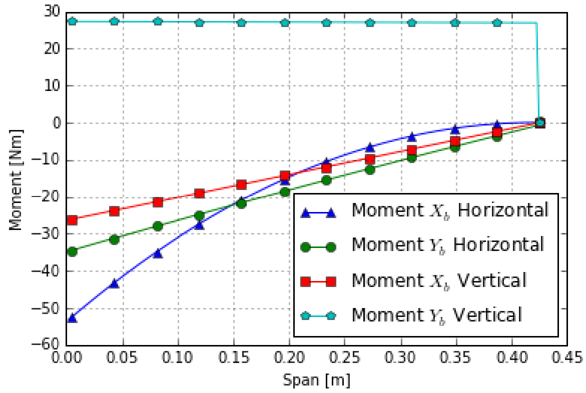
Material	Thickness [mm]
CFRP	0.4
Foam	15

9.6.5 Vertical Stabiliser Structural Design & Material Selection

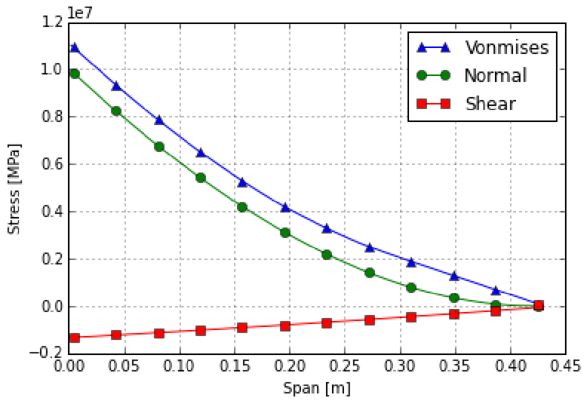
The vertical stabiliser was structurally analysed in a similar manner as the other wing types, for which Table 9.16 was used. The vertical tail too was found to benefit most from a lightweight combination between a carbon fibre tube and rectangular wingbox. The combination of both geometries at quarter



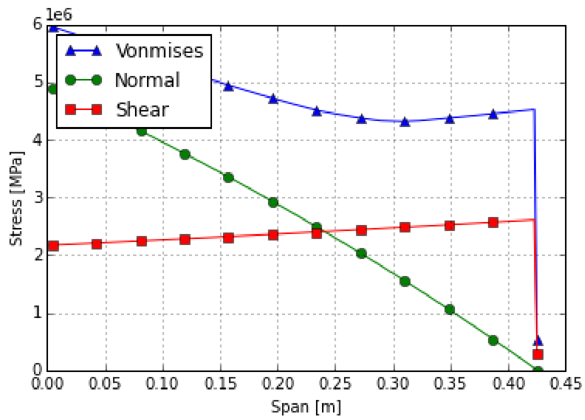
(a) Force Distribution



(b) Moment Distribution



(c) Stress Distribution - Horizontal Flight



(d) Stress Distribution - Vertical Flight

Figure 9.32: Load Distributions over Canard

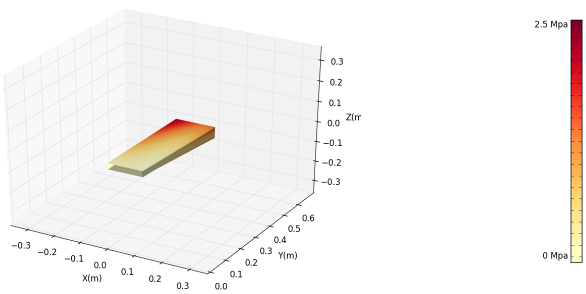
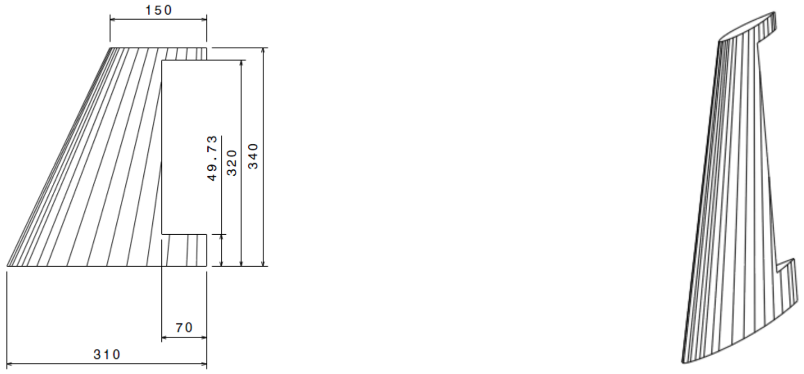


Figure 9.33: Von Mises Stress on Canard Wingbox

chord produced a highly stiff structure as for the main and front wings, experiencing almost zero deflection even at maximum load. For technical drawings of the tail please refer to Figure 9.34.

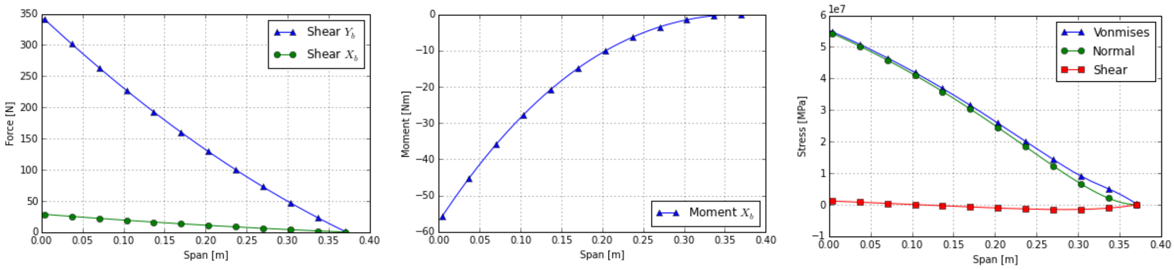
Foam was furthermore again implemented as the fill material for the vertical tail, fully determining the airfoil shape and was tasked with buckling avoidance of the thin-walled structure. The entire structure was sized to the maximum acceptable dimensions according to the size factors presented in Table 9.16. The total airfoil cross sectional area excluding thin-walled circumscribed areas was filled with foam.

Material selection was based on the same options as for the main wing. Please refer to Figures 9.35 and 9.36 for the relevant force, moment and Von Mises distributions over the wing span.



(a) Right View (b) Isometric View

Figure 9.34: Vertical Tail Geometry



(a) Force Distribution (b) Moment Distribution (c) Stress Distribution

Figure 9.35: Load Distributions over Vertical Tail

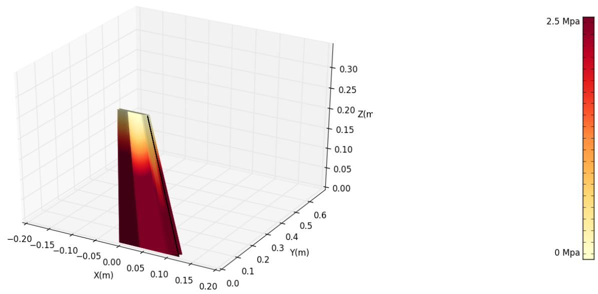


Figure 9.36: Von Mises Stress on Vertical Tail Wingbox

Table 9.16: Vertical Stabiliser Characteristics

Parameter	**Value**	**Unit**	**Parameter**	**Value**	**Unit**	**Parameter**	**Value**	**Unit**
Root chord	0.31	m	Lift/Drag	10	-	Wing span	0.37	m
Tip chord	0.16	m	Sweep	17	°	Engine loc.	-	m
ULF	12	-	Engine mass	-	kg	t/c	0.15	-
Lift	29	N	Engine thrust	-	N	Eng. strut l.	-	m
Wing box w.	40	%c	Wing box h.	10	%c	Wing box rad.	5	%c

Table 9.17: Mass & Cost Vertical Stabiliser Estimate

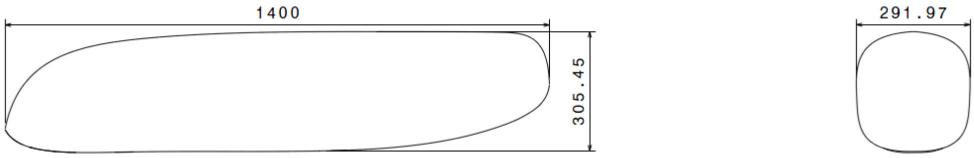
Structure Type	**Mass [kg]**	**Cost [€]**
Tubular	0.11	18
Structure Material		
Carbon		
Foam Material		
Airex		

Table 9.18: Vertical Tail Structure

Material	**Thickness [mm]**
CFRP	0.4
Foam	15

9.6.6 Fuselage Structural Design & Material Selection

The fuselage is the biggest and most critical structure of *Nora*, housing crucial subsystems such as the fuel engine and camera systems. Moreover, the fuselage carries all loads present in the entire body as the wings are connected to the fuselage at their respective locations. For information regarding the connectors and load introduction from wings to fuselage, please refer to 9.6.11. The fuselage structure is also under constant compression during horizontal flight due to the push propeller aft of the main wing. Please refer to Figures 9.37a and 9.37b for respectively the side and front views of the body and Table 9.19 for a general sizing overview.



(a) Side View of Fuselage (b) Front View of Fuselage

Figure 9.37: Scaled Fuselage Views

For maintainability and ease of use, the fuselage has multiple cutouts located at both the top and bottom halves, covering exactly 80% of the fuselage length. For an overview of the cutouts and their relative position, please refer to Figure 9.38. Cutout theory has been used to size the thin-walled fuselage structure [41], [42]. Through force equilibrium, it was found the shear flows resulting from the forces and moments acting on the fuselage had to be increased by a factor 7 to account for the increased stress because of the cuts.

Fuselage structural optimization resulted in a composite sandwich structure built-up from a CFRP shell covered in an Airex foam layer and Ultracote film protection against the weather circumstances. Please refer to Tables 9.20 and 9.21 for details regarding the fuselage structural characteristics.

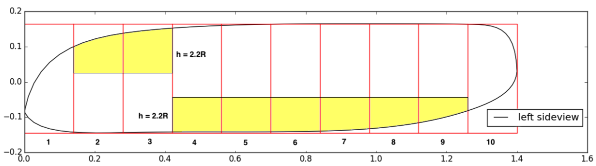


Figure 9.38: Fuselage with Cutouts

Table 9.19: Fuselage Characteristics

Parameter	Value	Unit	Parameter	Value	Unit
Maximum Radius	0.31	m	Maximum Z_b	0.15	m
Minimum Radius	0.00	m	Maximum Y_b	0.14	m
Length	1.4	m	Horizontal Thrust	65	N

Table 9.20: Mass & Cost Fuselage Estimate

Structure Type	**Mass [kg]**	**Cost [€]**
Tubular	1.80	1400
Structure Material		
Carbon		
Foam Material		
Airex		

Table 9.21: Fuselage Structure

Material	**Thickness [mm]**
CFRP	0.75
Foam	10

The internal structure of the fuselage will consist of a duct system, to accommodate for both cable handling throughout the fuselage and mounting of the different internal subsystems to the structure. Back of the envelope calculations have been done to check the feasibility of such a system, but a proper verification and validation will be done during the detailed phase. As a result of these back of the envelope calculations, the mass is estimated to be $120g$ and the cost is estimated to be €239 including material and production. This is for a duct system covering the same length of the fuselage as the cutouts. This is computed with a height of $100mm$, an average width of $15mm$ per duct and a contact surface of $30mm$ times the length of the duct, with $0.4mm$ CFRP. With $2kg$ per section, a safety factor of 2 and a load factor of $12g$, the duct will not be disconnected from the fuselage with uniform loading and middle aligned center of gravity per section. The material to connect the duct to the fuselage will be an epoxy adhesive like 5M KFL 162, with a peel strength of $2.5MPa$ and shear strength of $30MPa$.[8] The detailed design phase will optimise the duct structure to account for the different internal modular system and minimisation of mass and cost.

The fuselage contains a lot of components. These components have to be attached to the fuselage in some way. Because the fuselage is round, a carbon plate will be made in the fuselage such that all the components can be attached to it in an easy way. The fuselage has some cut-outs on the upper side and some cut-outs on the lower side of the fuselage. Depending on the position of these cut-outs the plate will either be a floor or a ceiling where the parts are attached to it. In Figure 9.39 an example is shown where the plate is acting as a ceiling where all the parts will be connected to. In total, the plates will weight $0.19kg$ and will have a surface area of $0.55m^2$.

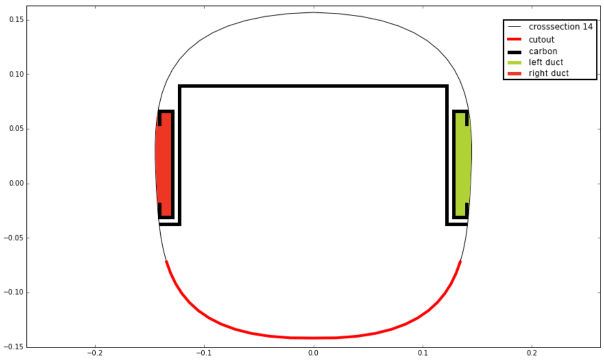


Figure 9.39: Cross section of the fuselage at $0.48m$ with the cutout, duct and tray indicated

9.6.7 Landing Gear Structural Design & Material Selection

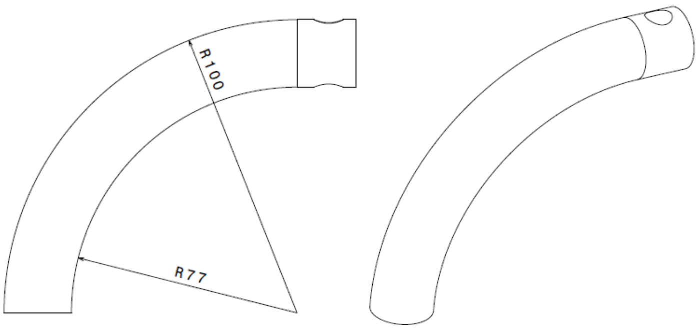
Nora's landing gear is based on the three legged principle of stability. Three legs are used to ensure the UAV is constrained in all three dimensions and is furthermore stable on any ground surface. The position of the landing gears have been determined based on *Systems Engineering and Aerospace Design* [43] and entail a nose landing gear position 15% in front of the most forward center of gravity limit while the main landing gear is respectively 45% behind the most aft center of gravity position, both based on horizontal flight conditions. Hence, the exact locations of the nose and main landing gears are $0.26m$ m and $0.96m$ respectively.

The design of the landing gears are all equal, and entail a simple non-retractable tricycle gear in the shape of a quarter circle; please refer to Figure 9.40. The quarter circle shape was deemed optimal for its wide base and capable of avoiding rocks on the ground during landing or takeoff. Moreover, the landing gear was designed to carry $11kg$ at an ultimate loading factor of $4g$ in order to provide *Nora* the capability for a hard landing if necessary. Please refer to Table 9.22 for the landing gear characteristics. It was found optimal to use a tubular ABS structure for the landing gears, which nowadays can be 3D printed at very low cost.

[8]URL http://www.5m.cz/en/epoxy-adhesives-high-strength/ [cited 12 June 2015]

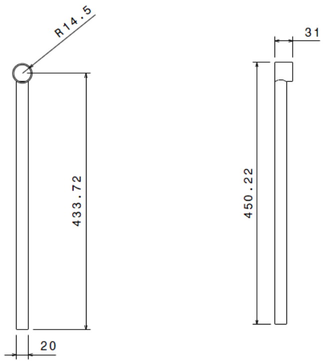
Table 9.22: Landing Gear Structure per Leg

Parameter	Value	Unit
ABS Thickness	1	mm
ABS Diameter	20	mm
Strut Radius	100	mm
Mass	0.038	kg
Cost	4.00	€



(a) Side view (b) Landing Gear Geometry

Figure 9.40: Landing Gear Geometry

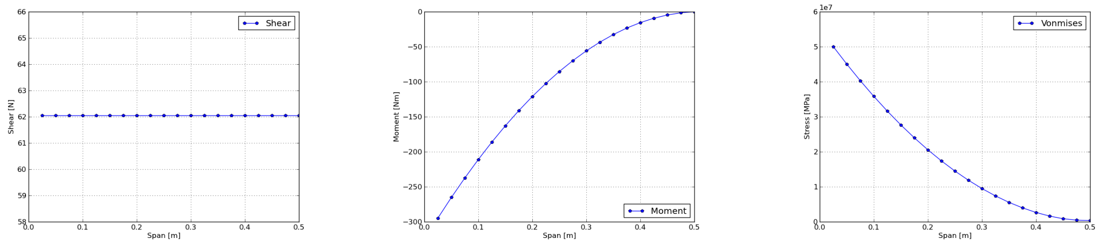


(a) Top View (b) Side View

Figure 9.41: Engine Mount Geometry

9.6.8 Engine Struts

Each of the four vertical takeoff and landing engines are connected to the relevant wings (i.e. either the canard or the main wing) via a connection rod, see Figure 9.41. These rods have been designed to account for the forces, moments and stresses present in the structure as outlined in Figures 9.42a, 9.42b and 9.42c respectively. The radius of each strut was found optimal at $0.02m$ while the thickness was optimized at $0.001m$, both for the carbon fibre Nylon-12 composite outlined in 9.6.2. This results in a strut mass of $0.053kg$ per strut and a cost of €258.



(a) Engine Strut Shear Force (b) Engine Strut Bending Moment (c) Engine Strut Stress

Figure 9.42: Engine Strut Structural Analysis

9.6.9 Verification

All individual modules of the main structural software have been tested separately as code and computation verification. A system test has also been conducted post facto in order to verify the entire software for a simplified beam to test whether the connections between individual code modules interact properly. For this combined testing module, a simplified cantilevered beam with zero sweep and zero taper was used as this is easy to quantify both numerically as well as analytically. Below, the verification results up to the stress calculations are presented as further optimization involves many iterations which are infeasible to complete analytically. The input values are specified below in Table 9.23.
Given that the geometrical properties of the test wing box are both constant with span location and equal to those of Table 9.23, the integration of the geometric properties has been found correct with

Table 9.23: Input Values for the System Test

Parameter	Unit	Value	Parameter	Unit	Value	Parameter	Unit	Value
c_r	$[m]$	1.0	L	$[N]$	98	L/D	$[N/m^2]$	10
c_t	$[m]$	1.0	n_{load}	$[-]$	10	t_{top}	[-]	0.010
Λ	$[°]$	0.0	L_2	$[m]$	0.50	t_{bottom}	[-]	0.010
b	$[m]$	2.0	m_e	$[kg]$	1.0	t_{front}	[-]	0.010
L_1	$[m]$	0.1	T_e	$[N]$	100	t_{rear}	[-]	0.010

(almost) zero error. For each function the output is compared to the analytical solution of the simplified beam. When the full code is executed, the following values for σ and τ are obtained in the midpoint of the bottom plate at the root as given in Tabel 9.24. The results show that the code approximates the analytical model very well, and any residual errors are mainly due to discretization and converge to zero with decreasing element size n.

Table 9.24: System Test Results

	Numerical	Analytical	Error
$\sigma(MPa)$	-54·10^4	-55·10^4	0.6%
$\tau(MPa)$	117·10^4	11·10^4	1.4%
$Y(MPa)$	58·10^4	58·10^4	0.4%

Table 9.25: Natural Frequencies

Type	$\omega_1[s^{-1}]$	$\omega_2[s^{-1}]$	$\omega_3[s^{-1}]$
Main Wing	0.0	22	30
Canard	0	14	17

9.6.10 Castigliano & Vibrational Analysis

A vibrational analysis was done to obtain an indication of the vibrational characteristics of the overall system. For the purpose of this first estimation the system is modeled as a mass spring system with three components: the fuselage and the wing as can be seen in Figure 9.43. The stiffness of the wings are represented in the equivalent spring stiffness as obtained from the structural analysis. The damping coefficients are inserted to dampen the vibrations even though the actual damping characteristics of the system are unknown. These, however, are perfect examples of parameters capable of being obtained through experimentation and validation of the model prototypes. The system has three degrees of freedom representing the possible directions of motion of the structure. A system of ordinary differential equations are then converted to a state space system to compute a first response to input disturbances. The disturbances expected in flight were computed using Castigliano's theorems to represent the deflections experienced in flight.

The natural frequencies of the system are shown in in Table 9.25. The natural frequencies of the main wing are quite high, this is mainly due to the high stiffness of the main wing. The canard, which has a relatively low stiffness, oscillates at a much slower rate and also experiences higher deflections. The eigenmodes and responses of the wing and canard can be found in Figures 9.44 to 9.46.

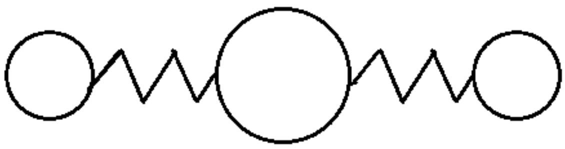


Figure 9.43: Mass Spring Model of the Aircraft Wings & Canard

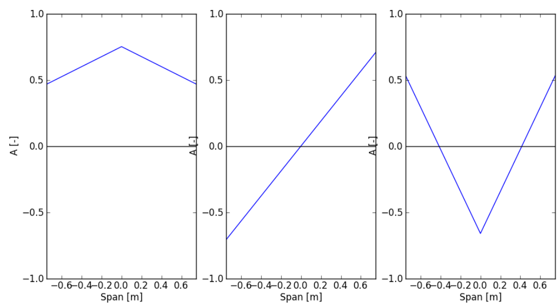


Figure 9.44: Normalised Eigenmodes of the Wing & Canard

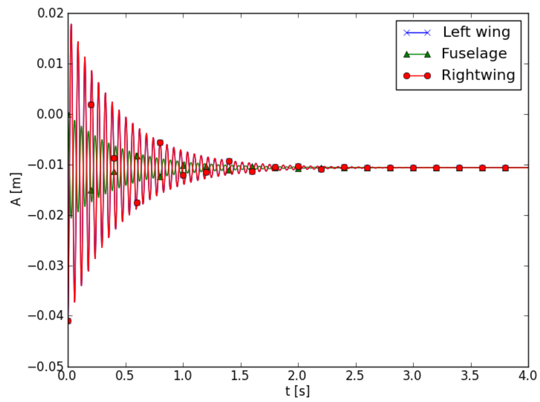


Figure 9.45: Canard Vibration with an Initial Deflection of A=−0.041m on Both Canards

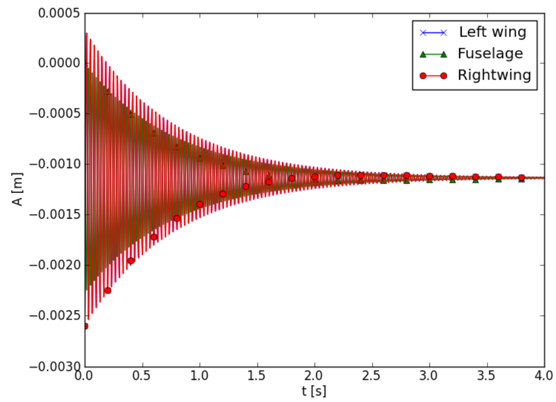


Figure 9.46: Wing Vibration with an Initial Deflection of A=−0.0048m on Both Wings

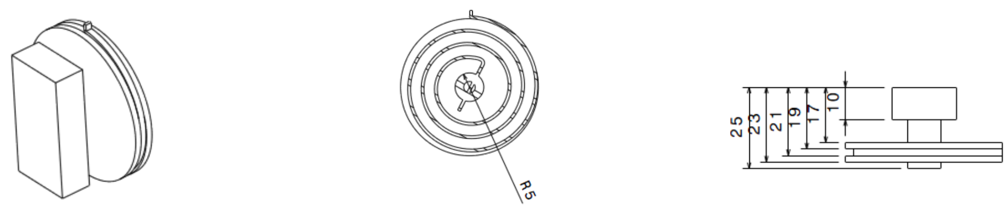
9.6.11 Separability & Connection Types

The structure of the aircraft is separable to allow for easy storage and handling by SAR personnel during missions. All large components that are linked to the fuselage such as the main wings, the canard as well as the tail are capable of being separated. The operator will connect the wings by pushing, sliding and finally locking the the structure into place. See Figure 9.48 for the connection mount.

The system depends on two spars in each individual wing, as was shown in Figures 9.28a. The main spar is located throughout the length of the wing, while the small spar is solely meant for connection purposes. A torsional spring is placed in the tubular spar and a rod connected to the spring can be pushed into a slot in the wing mount. By sliding the wing backwards, the rod is rotated due to the shape of the lock after which the rod reaches its place and rotates back, thereby trapping the rod in the lock. A separate pin can then be slid into the structure of the mount to fully lock the wing in place. In case the pin fails, the wing will not separate from the fuselage because the spring will still hold it in place. The spring system and the pin are displayed in Figures 9.47 and 9.49 respectively

Both the main wing and canard are locked in two places along the X_b axis to the fuselage in order to ensure a firm connection and avoid any twist around the Y_b axis. The tail however has one connection point, but is also supported by a cutout in the main wing mount.

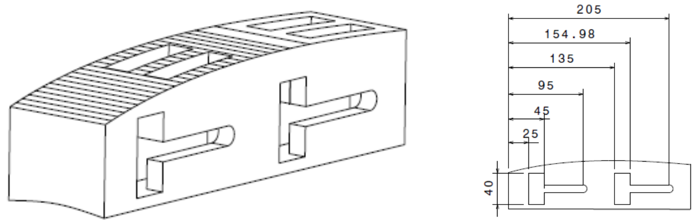
The stress and deflection analysis for the connections was performed in CATIA v5 and are shown in Figure 9.50. Load cases present were introduced to the connectors as the forces and moments located at the root of the relevant wing.



(a) Isometric View (b) Section View (c) Top View

Figure 9.47: Spring Connector

The connection mounts carry the loads of the wings which it connects to the fuselage; as such, the mounts need to have both high strength as well as high stiffness. For the fatigue life of the carbon fibre and foam cores of the mounts, please refer to Section 10.7. For this, again, stress analysis showed a sandwich structure using both CFRP carbon fibre reinforced Nylon-12 of 1mm thickness with an Airex C70-200 foam internal 10mm structure was the optimal design. This brings the total mass for five mounts up to 0.41kg with a cost of €305. The spring connector, as shown in Figure 9.47, has to transmit the loads



(a) Isometric View (b) Side View

Figure 9.48: Top Connection Mount

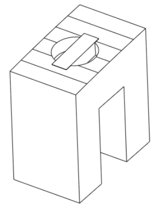


Figure 9.49: Connector Pin

from the wing to the mounts, and have been optimized based on stress analysis in material choice and thickness. A thin-walled titanium Ti-6Al alloy of 0.2mm will be used for these connectors, with a total mass of 0.11kg and a cost of €67.

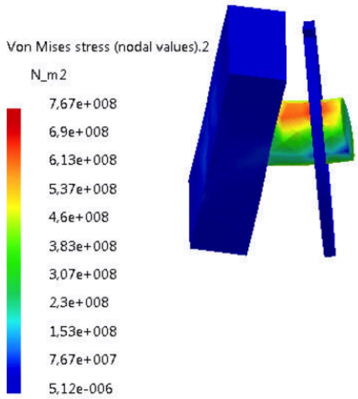


Figure 9.50: Stresses on the Connection Element

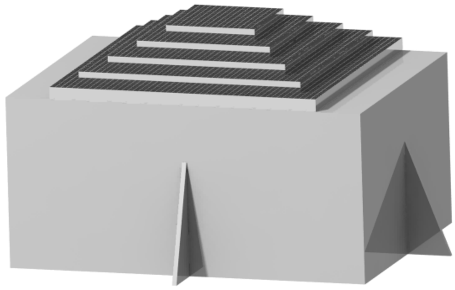


Figure 9.51: Impact Attenuator with Package

9.6.12 Production Plan

The production plan for Nora is closely related to the amount of units to be produced every year. Between 1 and 322 units will be produced every year as pointed out in Subsection 4.3. Production methods are chosen according to the part shape and material as well as the production. The production is split into two parts, the production of *Nora* and the production of the first aid package. These are separated because the first aid package is single use and could potentially be deployed every mission and is therefore considered to be a separate product. The production plan is schematically shown in Figure 9.52.

Production of Nora

The fuselage will be produced in two parts, split in the vertical axis along the longitudinal axis. The two halves will be produced by resin transfer moulding (RTM). In this way, the moulds can be reused. A drawback is low production rate, however, this corresponds to the amount of units to be produced. The two halves can be joined at a later stage with an extra layer of CFRP. The lifting surfaces will be 3D milled from Airex foam in two halves. In this way the internal structure and wiring can be installed before glueing the two halves together. The wingbox tubes and engine mounts will be CFRP produced by filament winding and the landing gear will be extruded with ABS plastic. There are several sub-assemblies that can be produced in parallel, thus decreasing the total production time. Engines, propellers, sensors, the fuel tank and the communication subsystem are off the shelf components that can be assembled into the structure after delivery. The connectors for the wings are produced from a sandwich panel with an Airex core and carbon fibre sheets.

Production of First Aid Package

The structure surrounding the first aid consists of sandwich panel of ABS and Airex, on top of that a D30 lightweight composite sheet and a corrugated aluminium sheet structure to protect the first aid kit's content during impact. The ABS sandwich panel can be produced by continuous sandwich production technique and cut in the desired dimensions. The aluminium sheet must undergo a series of bending operations to get the desired shape.

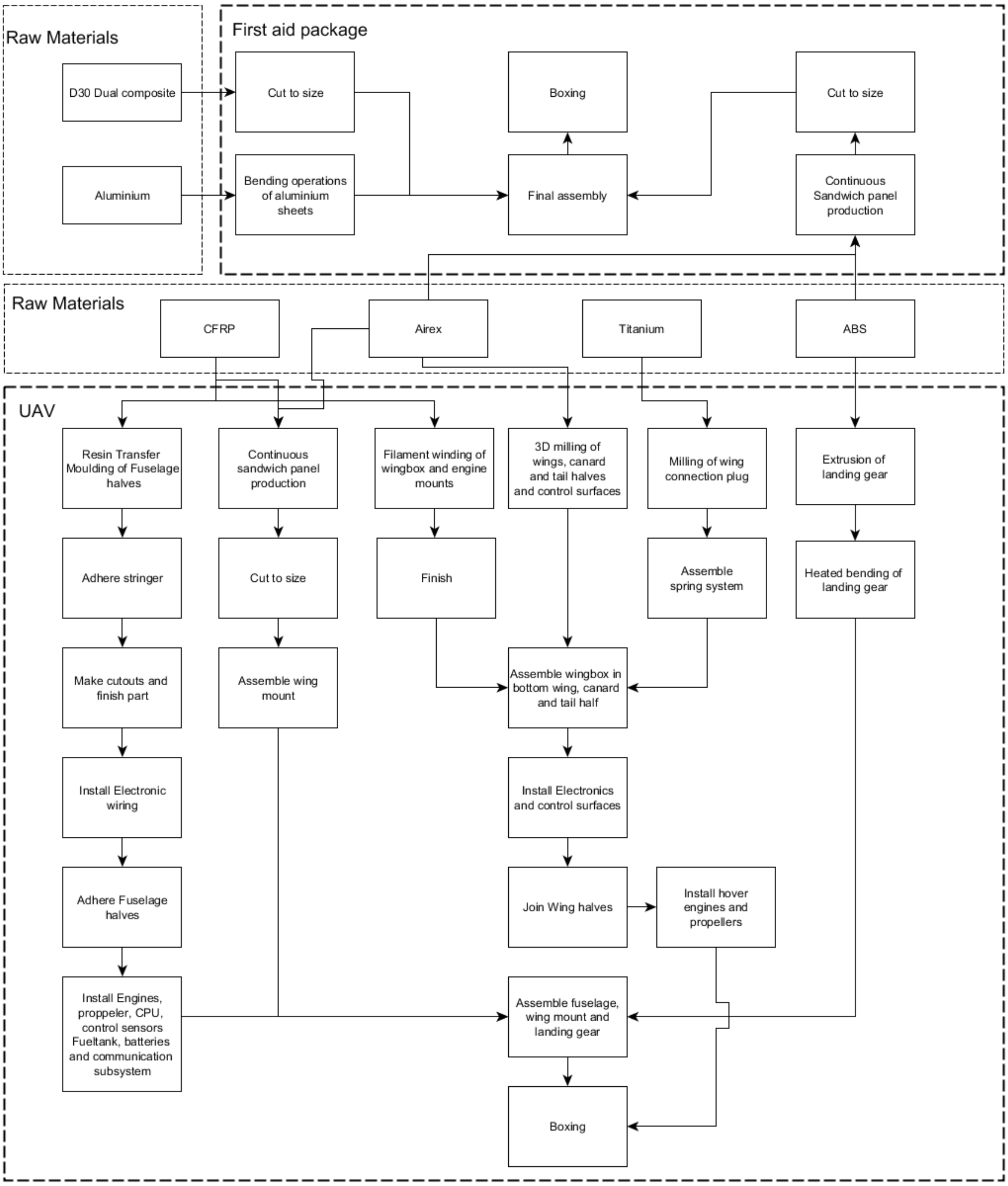


Figure 9.52: Manufacturing, Assembly & Integration Plan

9.6.13 Recyclability

As was described in Section 9.6.12, the structure is made using three materials. Airex C70-40 construction foam, which a standard cross-linked PVC material is used for the wings. The PA640 GSL isotropic carbon fibre is used for the fuselage and the internal structure of the wing. The entire structure will be covered using Ultracote. Furthermore the landing gear is made using Acrylonitrile Butadiene Styrene. When *Nora* is at the end of her lifetime the structure will have to be recycled. Multiple processes are used to achieve this.

Easiest to recycle is the Acrylonitrile Butadiene Styrene, since it is a thermoplast. The material can simply be heated and then blended with virgin material, to produce products with lower cost while preserving the high quality. [9]

The Airex C70-40 construction foam, is a cross-linked PVC material. Therefore it can be mechanically recycled. In this process the PVC waste is granulated into small pieces that can be easily processed into new plastics as reinforcement. In this process, the fine PVC powder can be used as filler in reinforced thermosets. [10] [11]

The PA640 GSL isotropic carbon fibre, should be re-used as much as possible. Since it is part of the internal structure it may well be that the system is still intact, when *Nora* is no longer able to fly. When this is not possible the carbon fiber can be recycled. The resin material of the composite consist of Nylon 12, which is a thermoplast. Therefore, when the material is heated, the Nylon will melt leaving the carbon fibers behind, making it possible to fully recycle the composite structure.[12], [13]

The Ultracote is not recyclable and should be thrown away. Whist removing the coating, part of the foam needs to be taken off and thrown away as well. When it is assumed that 5% of the foam is cut off whilst taking of the coating and thrown away together with the coating, 95.3% of the structure is re-used or recycled at the end of the life time.

Titanium used for the connectors can be recycled by melting the scrap into a titanium ingot either with or without virgin material. The melting process often employed is either vacuum-arc-reduction or cold-hearth methods.[14]

9.7 Package Delivery

For the delivery of the first aid package, *Nora* is planning to land next to the missing person to provide the person with a first aid kit. *Nora* landing is considered the best option in terms of accuracy and safety. It might not be possible to land in all situations. For these cases a package delivery system will be implemented. Although multiple options were considered in the *Mid Term Report* [3], the package drop with impact attenuator is considered the best option. Powered descent with two rotors is not stable, more rotors is too complex for a secondary delivery mode. Roped descent will pose risk to *Nora* when the rope length increases due to the dynamics of the full system. A parachute's descent is stable and safe, but due to the complexity, chance of getting stuck in trees, and a relatively high risk of deployment failure in flight, compared to other options, it was opted for package drop with impact attenuator.

9.7.1 Package Shell & Impact Attenuator

The package will be placed in a sandwich shell, to keep the content of the aid kit together, maintaining its shape to mitigate the risk of getting jammed in the UAV as well as provide a tough and impact resistant structure. For this sandwich structure, an outer layer of 0.4mm of ABS plastic and internal Airex C70-40 foam of 6mm was found optimal from stress analysis. In order to break the drop from heights up to 50m, an impact attenuator was designed. The impact attenuator working is based on the energy conservation principle. The kinetic energy before impact is transformed into internal energy, by buckling of the honeycomb structure. This honeycomb structure is made of T-7075 aluminium. The aluminium in the honeycomb structure has a thickness of 0.5mm. The honeycomb structure is made out of different segments in which a different amount of cells is used. This is done such that drops from different altitudes will still buckle some part of the structure such that energy is dissipated. There are five segments stacked

[9] ABS, URL http://www.plasticseurope.org/what-is-plastic/types-of-plastics-11148/engineering-plastics/abs.aspx[cited 18 June 2015]

[10] Foam recycling, URL http://www.recovinyl.com/pvc-recyclable-material-ideal-reprocessing[cited 19 June 2015]

[11] Nobel Prize Plastic Recycling, URL http://www.nobelprize.org/educational/chemistry/plastics/readmore.html [cited 29 June 2015]

[12] Carbon fibre 1, URL http://www.adherent-tech.com/recycling_technologies/carbon_fiber_reclamation_faqs[cited 18 June 2015]

[13] Carbon fibre 2, URL http://www.elgcf.com/recycled-carbon-fibre/the-process[cited 18 June 2015]

[14] Titanium Recycling, URL http://www.goldenrecycling.org/titanium-recycling.html [cited 28 June 2015]

on each other as can be seen in Figure 9.51. They consist of (from top to bottom) 16x16, 24x24, 32x32, 40x40 and 48x48. The weight of the impact attenuator is $0.320kg$ and it is capable of dissipating $480J$ which is equivalent to a 50% energy reduction for a drop from about $50m$. If the package is dropped from this altitude, the maximal g-force which the package experiences is $800g$ for a very short time ($2ms$). All the content in the package should be able to withstand this load for this amount of time. To give an illustration, a normal mobile phone is build to take up $2,000g$ for short amount of time. To make sure that the package lands on the impact attenuator, fins will be added which will keep the package pointing downwards due to aerodynamic forces.

Once the package has dropped on the ground, there is still a possibility that the package will bounce. To avoid this, the package is additionally wrapped in extremely efficient $10mm$ shock reducing D30 "Dual Composite" foam which is proven to reduce the impulsive force with up to an additional 80%. Combining the package attenuator with with this shock absorbing foam reduces the maximum load to only $160g$ over $2ms$. This is deemed sufficiently effective as package casing.

9.7.2 Package Aerodynamics

When the package is dropped, it is very important that the package will face down where the impact attenuator is, otherwise the design of the impact attenuator on one side would not be useful. In order to make sure that the package is dropped in the right way it will initially be dropped facing the right direction. Next to that, the centre of gravity of the package will be a bit more towards the desired face of the package. When an object is falling down, it is mainly its aerodynamics which determines the attitude of the object. Therefore, fins next to the package were added. Four triangular fins, one on each side, were added on the package such that the package will have the correct attitude on impact. The fins are designed such that it is stable when having the correct attitude and unstable when facing another direction, meaning that the package will always end up facing the correct attitude.

9.7.3 Fuselage Dropping Mechanism

The package will be dropped from the fuselage. This is done by opening the special hatch for the package. The action is triggered by a signal from the navigation and control PE, preceded by a command from the operator. The hatch is opened mechanically by a servo. The package is attached inside the fuselage of *Nora* to the top of the fuselage with a electro permanent magnet (EPM) with a capacity of $100N$. Once the hatch is opened, the EPM will release the package to be able to time the drop accurately. After a successful drop, the servo will return to its original position, closing the hatch. When the hatch does not open, the backup springs of the hatch can be used. After release from the EPM, the package will be able to fall through the hatch, without damaging the system. If the springs are too strong, the package may get stuck, but it is not considered a major problem since it is a secondary system.

9.7.4 Electronics

As described in the introduction of the section, the drone will consist of a light and sound emitting system combined with a positioning system that is able to communicate with the *Nora* system. Both the lighting system and the sound system are used to make the environment aware of the package that is being dropped. Normally, to indicate that there is a flying object, the lighting system will consist of a white light. Since the action is dangerous, a red strobe will be used instead of a white light. The on-switch will be triggered once the system is disconnected from the vehicle by checking the state of the quick release USB-port. After triggering the separation, the lighting system will start a red strobe light with blinking at $4Hz$. For the lighting system, the same visibility ranges will be used as by the lighting system of *Nora*. The sound system is used to create awareness of the package being there by means of a buzzer, but also that the drop might be dangerous. Thus only a piercing sound will be used to catch the attention of the missing person(s). The sound system will be designed for buzzers with the maximum available noise level at direct current. Therefore the $97dB$ Kingstate Surface Mount Electromagnetic Buzzer will be used. By using the sensors on the package, the lighting and sound system can be shut off, to make sure that the sound or lighting system will not cause any unnecessary harm to missing person(s).

For communication with *Nora* when the package is still in the vehicle a quick release USB connector will be used. This system works with USB 2.0 connectors and connects the lines with contact plates and magnets. Wireless systems were also taken into account, but eventually considered to complex for our type of robustness in operations and understandable techniques for the operators. To communicate with the UAS the communication device will be used that is included in the first aid kit. This handheld device will be chosen based on the connectivity with the proposed communication system of *Nora* as described in Section 8.1. Starting from the descent of the package, the UAV is able to receive the position coordinates of the package as measured by the sensors in the handheld device. Next to that, images from the phone can be received to analyse by the *Nora*'s detection PE. Based on this information, *Nora* might transmit a signal to the handheld that the lighting or sound system should be activated.

Normally, a PE for the package will be necessary to control the lighting and sound system and the communication system. Since there will already be a handheld device available, the handheld device will act as the PE of the package delivery parachute system. An example of such a device is the Nokia Lumia 435[15], which is capable of communicating via the $900MHz$ and $2.4GHz$ bands, with an accelerometer and GPS-receiver to indicate the motion and position of the package and a more than capable processor to process all information. Adaptions that should be made are mainly to the firmware to be able to have multiple devices connected to the USB port of the phone such as the lighting system and sound emitting system. Besides that, it should be able to share its power with these systems. Although an extra battery pack will be available for the powering of only the light and sound emitters. Additionally, it being Nokia, the phone will likely crack a rock rather than crack its own screen.

9.7.5 Contents of the First Aid Package

Nora will be able to deliver a $2kg$ package, by dropping it from the vehicle, as was explained in the previous section. The contents of this package can vary for different missions, depending on weather circumstances among other things. However, in this subsection, a basic set of supplies will be identified. When the missing individual is detected, it is a matter of time for the rescue teams to arrive. The primary task of the package is to make sure that the missing person can endure the time it takes for the operators to get to the missing person's location. The basic contents of the package can be found in Table 9.26 together with their dimensions, cost and weight.

Table 9.26: Standard Supplies of the First Aid Package

Item	**Weight (g)**	**Price (€)**	**Dimension (mm)**
Nokia Lumia 435	130	74.00	118.1x64.7x11.7
Phone Case	70	9.00	118.1x64.7x11.7
ISO Thermics Sleeping Bag	110	18.00	152.4x64
Self Heating Thermo Pad	160	8.50	127x25x76
Calorie bars (per 6)	240	2.25	76x38x95
Bottle of Water (500mL)	500	0.50	221x51
Water Purification Tablets (per 12)	90	7.80	-
Mountain First Aid Kit	700	24.00	200x120x90
Total	**2000**	**144.05**	320x230x150

The contents of the package can be divided into four categories. The first one the connection to the ground personnel therefore a mobile telephone will be included. As was explained in Subsection 9.7.4, a Nokia Lumia 435 is included in the package. A casing for the telephone is also available as extra protection for the impact of the package drop. Another important factor is making sure that the lost individual does not get under-cooled. The loss of body heat is a real danger especially in high altitude mountain terrain. To prevent this from happening a ISO Thermics sleeping bag and a self heating thermo pad by HEAT WAVE will be included [16], [17]. The third category is nutrition. A set of high calorie food bars from DATREX, will be included[18] These include 200 calories per bar and six of these bars will be included. Due to weight constraints of the package it is in most applications not beneficial to include a lot of water in the package. A bottle of 500 mL will be included. A set of water purification tablets

[15] Nokia Lumia 435 Specifications, URL http://www.microsoft.com/nl-nl/mobiel/toestel/lumia435/specificaties/, [cited 14 June 2015]

[16] Sleeping Bag, URL http://www.amazon.com/dp/B00XIO9HUY?psc=1[cited 16 June 2015]

[17] Survival Matches, URL http://www.amazon.com/Fantastic-Wind-Waterproof-Survival-Matches/dp/B007CP6UK0/ref=pd_sim_468_2?ie=UTF8&refRID=0HW3N4FJ38PMD2VZ9T72[cited 16 June 2015]

[18] DATREX, URL http://www.thereadystore.com/datrex-3600-calorie-food-bar[cited 16 June 2015]

will be added as well to purify water in the mountains. These tablets are produced by aquamira and kill 99.99% of the bacteria present in the water[19]. Moreover, a set of standard first aid supplies is inside, including tapes, bandages, scissors, medication and dressings. The exact contents of this first aid kid is derived from existing kits[20].

Figure 9.53 shows the system behind the phone connection of the victim with the SAR team through *Nora*. Note that lines indicate two-way links and arrows indicate one-way links. Power flow is indicated in red and flows towards the battery. The battery powers all other systems.

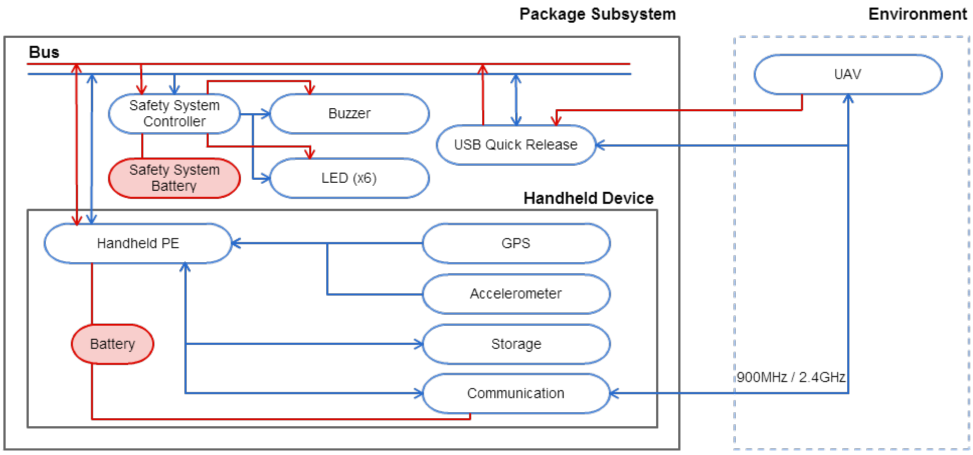


Figure 9.53: Package Communication and Power Diagram

9.8 Backpack Design

An important part of the mission is the rescue workers carrying *Nora* around. Therefore proper backpacks are of great importance to allow this first stage of the mission. In this section an indication is given about the backpack design.

Research into backpacks shows that at this moment two sorts of backpacks are relevant as reference for *Nora*: music instrument bags, and hiking backpacks. Instrument bags are promising due to their good protection capabilities, however they are far too heavy. Hiking backpacks are light, but do not necessarily offer good protection. Therefore a combination between a instrument bag and a hiking backpack is needed.

As can be seen from Section 6.6.4 the first responders, a team of 3 persons, can carry $8kg$ each. Therefore three backpacks must be designed. Within these $24kg$ there is $3kg$ contingency, $6kg$ of food, water and equipment (FWE), $1kg$ ground control system, $3kg$ for the backpacks and $11kg$ UAV. To equally divide the weight *Nora* is divided into eight fragments, which can be found in Table 9.27. All component weights can be found earlier in this Chapter and in Chapter 9. All the sensors and motors and other parts in the fuselage can still be taken out via the hatches, see Section 9.6. However when they are in the backpack, they must be inside the fuselage due to volume limits and for protection. Only the package is not inside the fuselage within the backpack as this would become too heavy. The wing and canard module both exist twice.
The largest fragment of *Nora* is the fuselage, which takes up $86L$. At this moment a $1.0kg$ backpack can carry along $69L$[21]. Therefore the weight for the fuselage backpack is estimated to be $1.3kg$ (no extra weight is estimated for protection such as padding from instrument bags, because weight is also saved due to less chambers, zippers etc). The fuselage itself weighs $6.35kg$, leaving room for $0.35kg$ of FWE. However this does not meet the required $2.0kg$ per person. This missing weight can be carried by one of the other backpacks. In Figure 9.54a it can be seen how the fuselage, food, water and gear would

[19] Water Purification, URL http://www.campingsurvival.com/aquamira-water-purification-tablets.html[cited 16 June 2015]
[20] First Aid Kit, URL http://www.gooutdoors.co.uk/lifesystems-mountain-first-aid-kit-p115141[cited 16 June 2015]
[21] URL http://www.ula-equipment.com/product_p/circuit.htm?avad=56397_f8f9e246, [cited 23 June 2015]

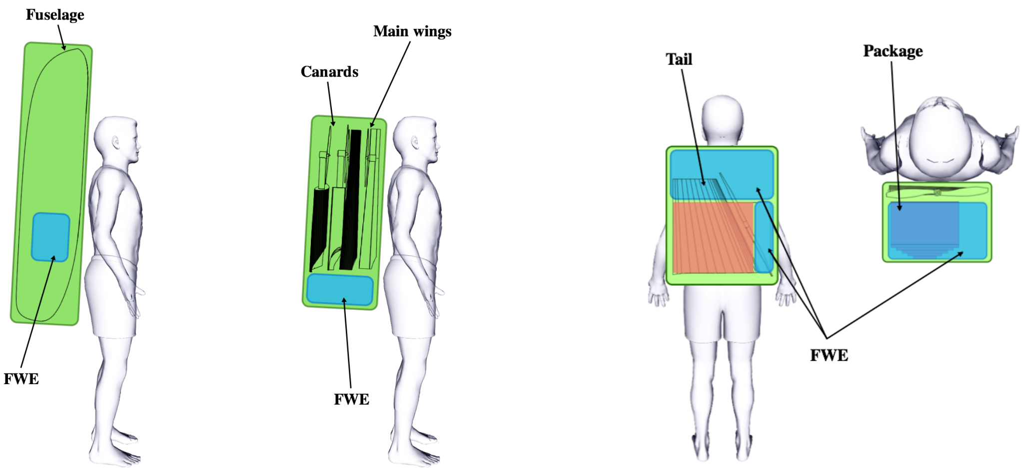
Table 9.27: UAV Modules

Fragment	Components	Mass [kg]	Dimensions [mm]
Fuselage	Detection system, control & communications, thrust engine, combustion engine, structure, generator, accu cell (6x), hover engine (4x), landing gear, slots (3x), duct system	6.35	1400x3055x291
Wing	Hover propeller, structure, locking system (2x), engine strut, aileron servo	0.57	575x720x70
Canard	Hover propeller, structure, locking system (2x), engine strut, elevator servo	0.37	450x425x55
Tail	Structure, locking system, rudder servo	0.13	340x310x40
Propeller	Main propeller	0.02	400x60x40
Package	Shell, attenuator, package content	2.60	320x240x201

be distributed over the backpack. Since a $3.0kg$ contingency was chosen and only a mass of $7.0kg$ was allocated, the remainder can be filled with anything that meets the searcher's needs.

The second backpack is filled with the two wings and the two canards, and is therefore called the wing backpack. Together this is $1.9kg$. This backpack must be $0.9kg$, since it will have a smaller volume, but the weight is still needed for extra protection of the rotors as they are the most vulnerable. This leaves $5.2kg$. From this $1kg$ is reserved for the ground control system and $1.5kg$ is reserved for contingency. Now $2.7kg$ is left for FWE. The contingency space can always be filled with extra fuel for *Nora* or with extra water, food or equipment. How these components are placed can be seen in Figure 9.54b.

Lastly the remaining components are in one backpack, the package backpack which can be seen in Figure 9.54c. This backpack contains the package, the tail and the main propeller,which take-up $2.8kg$. The backpack itself will weigh $0.8kg$, which is slightly less then the wing backpack. This is due to the fact that slightly less padding has to be used and less volume is needed. This leaves room for $2.9kg$ for FWE and (again) a $1.5kg$ contingency space.



(a) Fuselage Backpack (b) Wing Backpack (c) Package Backpack

Figure 9.54: Backpacks of *Nora*

9.9 Final Layout

This section shows and summarises the final layout and configuration of *Nora*. First of all, a graphical outline will be given by means of a 3D render of *Nora* (Figure 9.55). This is accompanied by Figure 9.56 showing an overview of the internal layout, where all subsystems are located. Finally, the most important design characteristics that were discussed over the previous chapters are listed in Table 9.28

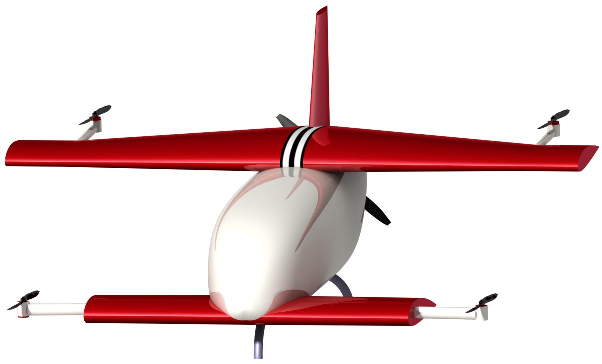


Figure 9.55: *Nora*'s External Layout

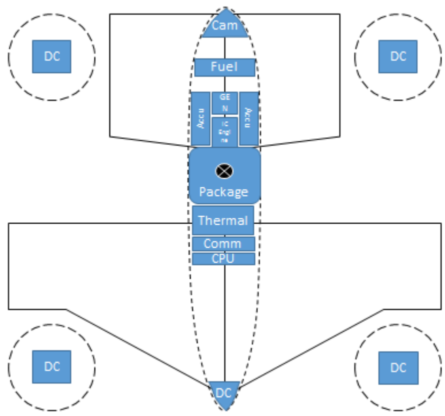


Figure 9.56: *Nora*'s Internal Layout

Table 9.28: Summary of *Nora*'s Characteristics

Component	**Description**
Overall System	$15kg$ system mass, $11kg$ vehicle mass with $1.5m$ maximum span $2h$ up to $6h$ endurance Separable over 3 backpacks for ground transport
Wings	Canard configuration with vertical stabilizer Optimised for aerodynamic efficiency Longitudinal and directional stability Elevators, ailerons & rudder powered by 8 servos for attitude control
Power & Propulsion	Hybrid fuel-electric propulsion ($2,200W$ power, $2.7kg$ subsystem mass) Vertical Take-Off & Landing (VTOL) $0.57kg$ design fuel weight, room for up to $1.00kg$ $7200mAh$ accumulator for $2min$ pure electrical flight
Materials	Carbon fibre nylon-12 composite for lightweight structural integrity Airex foam for impact resistance, shaping and structural support Ultracote coating for weather resistance and smoothness Ti-AL6-V4 Titanium alloy for strong & light wing connector
Structure	Unibody fuselage design of $1.8kg$ Cutouts spanning 80% of the length for easy accessibility Structural mass of $0.45kg$ per main wing, $0.26kg$ per canard wing and $0.11kg$ for the vertical stabilizer Click-Slide-Go connectors for short operational preparation time Landing gear for protection of the structure
Detection	Thermal & optical imaging and radio frequency detection Detection altitude of $241m$ Nominal ground coverage of $20.4km^2h^{-1}$, up to $34.6km^2h^{-1}$ Radiofrequency detection of mobile phone and RECCO signals Autonomous detection fed back through intuitive tablet user interface
Embedded systems	Both line of sight and satellite communication Three antenna types for optimal data transfer at all LOS ranges USB 3.1 subsystem connections for ease of use and adaptability Separate PID flight controllers for hover and cruise $128GB$ storage dedicated to visual detection systems $128GB$ storage dedicated to flight parameter recording (black box) $128GB$ storage for all other subsystems
First Aid	Contains medical supplies, nutrition, thermal gear & phone Provides comfort & radio contact to the victim Delivery by landing or altitude drop Impact attenuator reducing impact energy by 70%

10 | Design Evaluation

A logical step following the design is the assessment of the design. The chapter starts out with *Nora*'s cost, mass and power budget in Section 10.1. Secondly, in Section 10.3, the performance of *Nora* is analysed, succeeded by the sensitivity in Section 10.4. A requirement compliance matrix is constructed to check whether the design meets the requirements in Section 10.5. Afterward Risk is touched upon in Section 10.6 and RAMS analysis is performed in Section 10.7. Finally in Sections 10.8 and 10.9 the return on investment is elaborated upon and the sustainability of the design is outlined, respectively.

10.1 Cost, Mass & Power Budget

In the following section the cost, mass & power breakdown of *Nora* are presented. In Table 10.1, for each subsystem the total costs, mass and power can be found and in Table 10.2 the operation budget breakdown can be found. A few things should be noted when reading this table. First of all the communication subsystem has multiple expansion possibilities. The standard package used for Europe is presented within the table. A more detailed explanation of the communication subsystem can be found in Section 8.1. The detection subsystem only includes the thermal and optical imaging method. The radio frequency sensor system is implemented in the communication subsystem as it uses the same antennas (section 8.2.3). The sound senor package will be an extension once the technology has been developed sufficiently, as is explained in Section 8.2.2.

The cost breakdown is purely based on the cost of the different subsystems. A more detailed explanation of all expenses is given in the return of investment section 10.8. However a distinction has been made between the vehicle cost and the operational costs, that have to be paid each mission. Each mission has a duration of 2 hours, as was established in the requirements. Table 10.2 shows, the cost and mass of all components that can be replenished. Especially the contents of the package do not need to be replaced after each mission since not all supplies will be used. Moreover, the package will not be dropped in each mission, reducing the operational costs even further. The €256 is therefore an absolute maximum. If it is assumed that for 20% of the missions the package is dropped, because the vehicle is not able to land and 25% of the package content is replaced after each mission, an operational cost of €105 is achieved for a two hour mission. This is equivalent to €52.5 per hour. Figure 10.2, shows the cost distribution for both the vehicle and the operational cost. Furthermore the mass distribution can be seen in Figure 10.1. For the power budget no distribution pie chart was made as the propulsion system uses 99.7% of the needed power and a visual representation would be nonsense.

Table 10.1: Component Budget Breakdown

Subsystem	**Price [€]**	**Mass [kg]**	**Power [W]**
Propulsion	470	2.1	7100
Structures	3900	4.5	-
Detection	7400	0.61	12
Control	320	0.030	1.4
Collision Avoidance	120	0.13	44
Data Handling	310	0.30	0.030
Communications	1200	0.14	5.3
Total	**13720**	**7.81**	**7162**

Table 10.2: Operational Budget Breakdown

Part	**Price [€]**	**Mass [kg]**	**Effective Price [€]**
Fuel	0.81	0.57	0.81
Package Shell	41.00	0.28	8.20
Package Attenuator	13.00	0.32	2.60
Package Content	140.00	2.0	36.00
Satellite Communication	38.00	-	38.00
Maintenance	20.00	-	20
Total	**253**	**3.17**	**105.61**

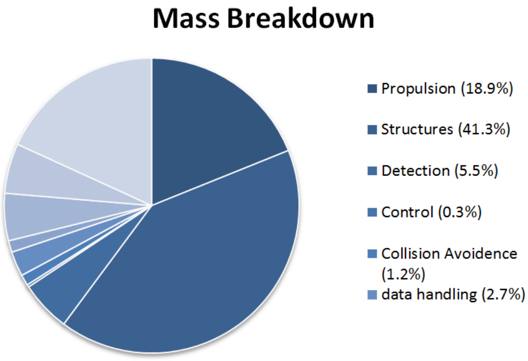
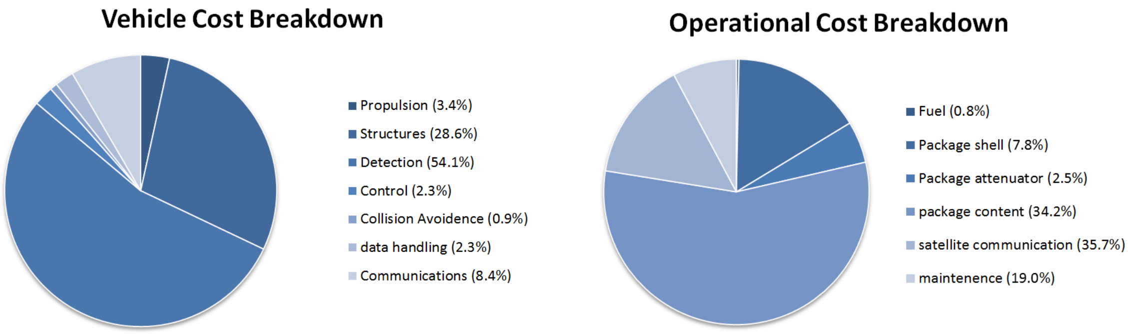


Figure 10.1: Mass Breakdown



(a) Vehicle (b) Operations [per 2*hour* mission]

Figure 10.2: Cost Breakdown

10.2 Sample Mission Profiles

In order to give the reader an idea of how *Nora* is going to function in the real world, an example mission will be described. A whole fictitious story about a missing person will be written below in order to give even more feeling about the function that *Nora* will fulfil.
A small story Meet John, John is an amateur hiker. He is 45 years old and has two children and a lovely wife. Together with his family John is on holiday in Lienz in the Alpes. John prefers walking through the mountains on his own, because his wife walks too slow and his children just can't seem to stop whining. Besides it is a great opportunity to clean his mind from the stress at work.

At 7:00 John walks out the door and promises his wife to be back around 3pm to go to local market. Around 10:00 John drinks a cup of coffee in a local hiking hut and has a friendly conversation with the waitress. Then he continues on his journey. Around 12:00 John realises he must have taken the wrong path and walks back trying to find a scenery he is familiar with, but after thirty minutes he still hasn't found his old path. He decides to call his wife but soon realises he does not have mobile connection. He decides to walk towards a valley hoping to find someone that is able to tell him which direction to go to.

Meanwhile John's wife is enjoying her day. Her kids are playing somewhere with their friends and she finally has time to read her book in peace. At 14:45 she picks up to kids from the playground to get ready to go to the market. Thirty minutes later John is still not home and she is slowly getting annoyed. She calls him, but she is not able to reach him. Around 16:00, she calls again and when she still can't reach John, is starts to worry. At 17:00 she calls the local SAR team. She is told that if her husband is not home within an hour they will start a search mission.

At 17:00 the SAR team starts gathering information on the whereabouts of John, just in case he is indeed missing. At 18:00 they move towards the hiking hut John was last seen by car. However the road does not get them there entirely, so they start walking where the road ends. 19:20 the SAR team launches *Nora*. The spiral search was chosen, with the staring point at the Hiking Hut and a radius of 7.5km. When using a larger radius, *Nora* would already reach roads and villages, which is of course unnecessary. Using a spiral search flight pattern for the entire area will take $10.5h$ and a distance of $1138km$ will be travelled. Therefore the SAR personnel decides to first use the spiral mode only on one side of the mountain, because that is where John was last seen. When this is done $197km$ has to be travelled to cover an area with a radius of $6.1km$ can be searched within $1.8h$.

After 90 search minutes *Nora* detects a human being, which is identified to be John by the search and rescue personnel. John is sitting near a river. Due to the large amount of trees and the water, landing is not possible. Therefore a package is dropped. John is able to eat and drink something and uses the sleeping bag to keep himself from getting hypothermia. Moreover he is able to use the mobile phone, which is in connection with *Nora*, to communicate with the search and rescue team. After he has been found it takes the SAR team an hour to get to his location. At 21:50 they arrive at his location. From here it still takes $40min$ to get to the car that will finally return John to his wife and children at 23:00.

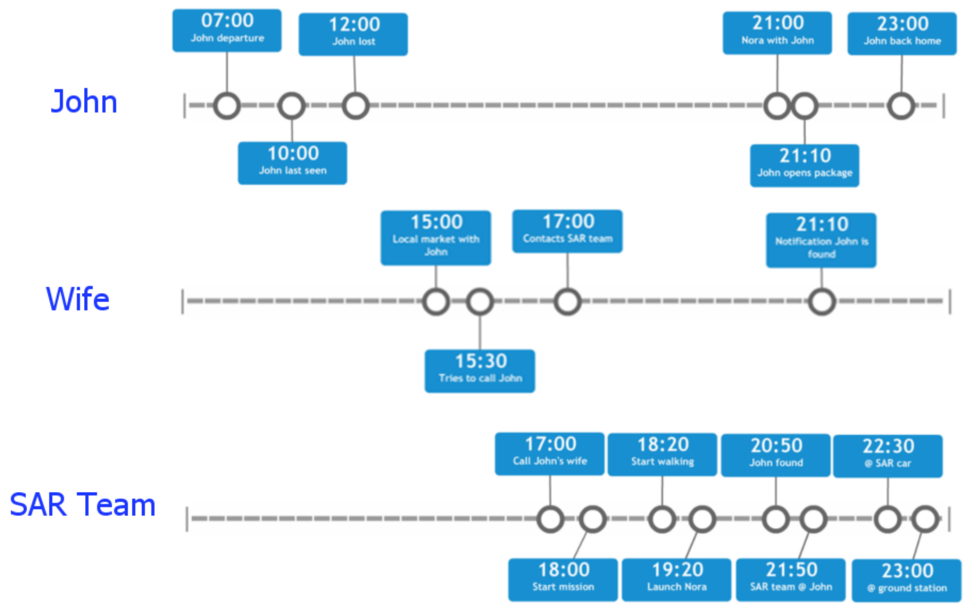


Figure 10.3: Timeline of a Sample Mission

10.3 Performance Analysis

To test whether requirements are met with respect to flight performance and sustainability, this section will discuss the the different performance indicators of *Nora*. The performance indicators that will be discussed are the area coverage, endurance, climb rate, climb angle, stall speed, maximum speed, turn radius, emission of carbon dioxide and noise. Firstly, the method of calculation is outlined. Afterwards, all results are summarized in Table 10.3. Note that all the values calculated in this section are the absolute maximums and may not be continuously achievable.

The area coverage, as explained in Subsection 8.2.1, can be computed by multiplying the distance travelled in one hour with the swath width. Together with area coverage, the endurance determines the overall search area covered by *Nora*. The endurance of the device was one of the most important design parameters. *Nora* was required to have an endurance of at least two hours. The actual endurance is dependent on the mission profile, because certain manoeuvres require more power than others. The mission for endurance calculations was defined to have of $30min$ of hover time, performing cruise flight for the remaining flight time and adding an additional fuel reserve of 20% for manoeuvring. Filling the fuel tank with $0.57kg$ making *Nora*'s total mass of $11kg$ resulted in an endurance of $2h$. With a full fuel tank ($1kg$ of fuel) the total mission endurance was shown to go up to $6h$

Thirdly, the rate of climb of an aircraft can be calculated using Equation 10.1. The thrust characteristics of the engine and propeller combination are known which means that that the thrust and power available are known. Besides, the lift coefficient required to stay airborne can be determined from which the appropriate drag coefficient can be determined. This gives us the drag at a certain velocity. Doing this analysis at multiple speeds gives the maximum climb rate. The determination of the climb angle is similar to that of the climb rate, using Equation 10.2.

$$rc = \left(\frac{T-D}{W}\right)V \qquad (10.1)$$

$$\gamma = \arcsin\left(\frac{T-D}{W}\right) \qquad (10.2)$$

Two additional important parameters are stall speed and maximum speed of the aerial vehicle as they determine speed range at which it can fly. In practice *Nora* was designed to be able to hover which makes the effective stall speed $0ms^{-1}$. However an indication of the stall speed in cruise flight mode is still very useful. The stall speed is effected only by the air density according to Equation 10.3. All other symbols represent known constants. The maximum speed can be easily determined by comparing the available thrust and the drag that is present when trying to maintain level flight.

$$V_{stall} = \sqrt{\frac{2mg}{\rho S C_{L,max}}} \qquad (10.3)$$

$$\theta = \cos^{-1}\left(\frac{mg}{L}\right) \qquad (10.4)$$

$$r = \frac{V^2}{g\tan\theta} \qquad (10.5)$$

The radius of a banked turn is described by Equation 10.5. There are several limitations that affect the radius that should be taken into account. First of all the maximum lift at which a steady turn can be performed at a certain speed. This limits the turn radius at higher speeds because flying at $C_{L_{max}}$ would mean that the drag is higher than the thrust resulting in an unsteady turn. Secondly the maximum load factor should not exceed $8g$ due to structural limitations. To determine the minimum turn radius the propellers where turned on during normal flying conditions. The performance of the rotors was estimated to be minimal under these conditions and therefore the thrust was estimated to be 50% of that available at $5,000m$. This resulted in a turn radius of $28m$ at $5,000m$ and $16m$ at sea-level. Finally it is interesting to note that the turn radius at the cruise speed of $30m/s$ is $33m$ at $5,000m$, and this radius only decreases with decreasing altitude.

Due to the high altitude and climate variations, *Nora* should be able to operate in a wide range of temperatures from $-40°$ up to $60°$. This range has an influence on the different components in the system. A more elaborate explanation of the cooling can be found in section 9.3. Regarding low temperatures, most of the electronics can cope with these, except for the combustion engine. Pre-start heating is done using an electrical heating system which draws current from the accumulator into some resistors close to the engine. Once the combustion engine is started, it will heat itself. In the wings there are heating elements as well for de-icing purposes embedded in the C70-40 foam, which is capable of temperatures up to $80°C$. In warm conditions, the combustion engine will need cooling as well. Air, redirected to flow next to the combustion engine, is used for this purpose. The generator and the rear engine need to be cooled as well with air cooling. The accumulator is not cooled as it can cope with high temperatures and will not heat up significantly. All low power electronics are connected to the same cooling system but the cooling requirement for these components is much lower.

The carbon dioxide emission of *Nora* is based on the CO_2 output of burning a full tank of fuel. A full tank of fuel consists of approximately $1kg$ of gasoline. Gasoline consists of 82.5% carbon. This means that a fuel tank contains $0.83kg$ of carbon. To burn this amount of carbon $2.2kg$ of oxygen is needed. This means that burning one tank of gasoline amounts to $3.0kg$ of CO_2 emissions.

Table 10.3: Performance Analysis - Results

Performance Characteristic	Value	Unit
Area coverage	21	km^2h^{-1}
Endurance	350	min
Maximum climb rate	33	ms^{-1}
at cruise speed	*53*	ms^{-1}
Maximum climb angle	48	°
at cruise speed	*34*	ms^{-1}
Stall speed (sea level)	15	ms^{-1}
Stall speed (5000m)	20	ms^{-1}
Maximum speed	83	ms^{-1}
Minimum turn radius (sea level)	28	m
Minimum turn radius (5000m)	28	m
CO_2 emissions (1kg fuel)	3.0	kg

10.4 Sensitivity Analysis

As stated many times before, the versatility under a wide range of conditions is essential for the success of *Nora* as a product. As such, she should not be too susceptible to small variations in operating conditions. Therefore, the sensitivity of *Nora* with regard to several aspects has been assessed. In order of description, these are sensitivity regarding power & propulsion, detection and structure.

10.4.1 Power & Propulsion

The first sensitivity analysis that was done concerned the power and propulsion system. In this analysis some driving parameters were altered in order to check what the effect on the design would be. The results can be found in 10.4. When changing the parameters the engines have to be changed, but not in all cases these have to be changed, this could mean that the change in weight is very small. One can see that the vehicle mass has a big influence on the power and propulsion weight. All the efficiencies have an almost linear influence on the weight of the fuel. The diameter of the rotor and propeller have a big impact as well. The maximum altitude does not change anything in the design when changing only 10%. This means that the current design is able to fly higher and still meet the requirements.

Table 10.4: Power & Propulsion Sensitivity Analysis

	Propulsion Mass *+10%*	Fuel Mass *+10%*	Prop. Mass *-10%*	Fuel Mass *-10%*
UAV mass	+17%	+8.9%	-2.4%	-8.9%
Energy	+1.4%	+10%	-1.4%	-10%
Combustion engine efficiency	-1.3%	-9%	+1.6%	+11%
Propeller Efficiency	-0.6%	-9%	+16%	+11%
Electrical engine efficiency	-1.9%	-9%	+2%	+11%
Max Altitude	0%	0%	0%	0%
Max hover acceleration	+12%	0%	0%	0%
Rotor diameter	-0.9%	-1.2%	+16.6%	+5.1%
Propeller Diameter	0%	-0.8%	+16.6%	+3.4%

10.4.2 Missing Person Detection

Secondly, a sensitivity analysis for the thermal and optical imaging detection system was performed. Parameters assessed are the number of pixels by Johnson's criteria as well as the critical dimension of the target. The impacts of variations of ±10% may be found in Table 10.5. Parameters selected for detection sensitivity analysis include the altitude at which *Nora* may operate, ground coverage during detection search phase, the field of view range across track and the minimum required angular velocity of the image pointing system along track. Changes of output parameters are found to be close to the initial alteration, thus showing relatively linear behaviour, except for the required fields of view for detection and identification. This means that the margin for zoom remains available, although the altitude at which the detection takes place may change due to modified Johnson's criteria or critical dimension requirement. Concluding, the imaging detection system may be relatively simply adapted to required changes in search criteria, admittedly affecting operational parameters, yet leaving the very system unchanged. One point of attention is however that the servos used should be well within change limits.

Table 10.5: Missing Person Detection System Sensitivity Analysis

	Johnson's Crit. *+10%*	**Critical Dim. *+10%***	**Johnson's Crit. *-10%***	**Crit. Dim. *-10%***
Maximum altitude	-9.1%	+10.0%	+11.1%	-10%
Ground coverage	-9.1%	+10.0%	+11.1%	-10%
Maximum FOV across	0%	0%	0%	0%
Minimum FOV across	0%	0%	0%	0%
Minimum servo turn	+10%	-9.1%	-10.0%	+11.1%

10.4.3 Structure

Finally, a sensitivity analysis for the structure was executed. In this analysis, structural design driving parameters have been altered in order to check what the effect on the eventual design would be. The results can be found in 10.6. As before, a change in structural mass was implemented with either positive or negative steps of 10%. As is clear, the structure has quite extensive impact on the overall performance of *Nora*, with a strong influence on total vehicle mass and required vertical thrust. Furthermore, it should be clear that applying additional positive sweep on the wings has a beneficial effect on the structural mass as load relief starts playing an important role in that case. Lastly, it can be seen the structural mass and engine weight are unrelated in this analysis as this relationship is more obvious in the power and propulsion sensitivity.

Table 10.6: Structure Sensitivity Analysis

	Structural Mass *+10%*	**Structural Mass *-10%***
UAV Mass	+37%	-42%
T_{vert}	+40%	-56%
C_r & C_t	+20%	-23%
b	+21%	-22%
L_{fuse}	+20%	-20%
Λ	-42%	+41%
m_{eng}	0%	0%
Cost €	+23%	-19%

10.5 Requirement Compliance

This section deals with the requirement compliance of *Nora*'s design. The section is divided into three subsections, respectively the requirement compliance matrix, the project guide compliance as well as an explanation of unmet requirements.

10.5.1 Requirement Compliance Table

In the following section the requirement compliance table will be presented. All requirements set in *Baseline Report* (and adjusted during the *Midterm Report*) are checked for the required output.[2, 3] This is shown in table 10.7. The key, driver and killer requirements are indicated by [KEY], [DRV] and [KIL], respectively. The requirements that are not met are provided with a cross and will be further elaborated upon in Subsection 10.5.2. Using the ID of the requirement the type of requirement can be distinguished.

Table 10.7: Requirements Compliance Matrix

ID	Requirement	Desired output	Design output	
MH-SH1-01	The system shall find the missing person(s)	✓	✓	✓
MH-SH1-02	The system shall be able to provide first aid help to at least three missing persons	✓	✓	✓
MH-SH1-03	The system shall not inflict further injury to the missing person(s)	✓	✓	✓
MH-SH1-05	The system shall find the missing person(s) as soon possible	✓	✓	✓
MH-SH1-06	The system shall provide first aid help	✓	✓	✓
MH-SH2-02	The system shall provide the missing person(s) location	✓	✓	✓
MH-SH2-03	The system shall provide its location to the SAR team	✓	✓	✓
MH-SH2-04	The system shall be portable by one or more searchers	✓	✓	✓
MH-SH2-06	The system shall be operable with no more than one day of training	✓	✓	✓
MH-SH2-07	The system shall be be operable in the same weather conditions as the SAR team	✓	✓	✓
MH-SH2-08	The system shall fly for at least thirty minutes	$30min$	$2h$ up to $6h$	✓
MH-SH3-01	The system shall include at least one aerial device	✓	✓	✓
MH-SH3-02	The system shall have an operational cost lower than 50% of a helicopter	€ 1650 per hour	€ 52.5 max per hour	✓
MH-SH3-03	The system shall require a maximum of 0.5 maintenance man-hour per flight hour	✓	✓	✓
MH-SH4-01	The system shall deliver a first-aid kit to the subject	✓	✓	✓
MH-SH4-02	The system shall inflict no additional harm to anybody	✓	✓	✓
MH-SH4-03	The system shall provide information about the condition of the victim	✓	✓	✓
MH-SH6-01	The system shall limit the release of dangerous substances	✓	✓	✓
MH-SH6-02	The system shall be 50% more quiet than a helicopter	$100dB$ at $30m$	$66dB$ at $30m$	✓
MH-SH6-04	The system shall not endanger the local population during its operations	✓	✓	✓
MH-SH6-05	The system shall not induce avalanches	✓	✓	✓
MH-SH7-01	The system shall provide real-time progress information	✓	✓	✓
MH-SH7-02	The system shall improve SAR search time	✓	✓	✓
MH-SH8-01	The system shall ensure the safety of all	✓	✓	✓
MH-SH8-02	The system shall comply with national and international law in the area of operation	✓	✗	✗

ID	Requirement	Desired output	Design output	
MH-SH9-01	The system shall provide real-time progress information	✓	✓	✓
MH-SH9-02	The system shall feel trustworthy	✓	✓	✓
MH-SH11-01	The system shall not damage property	✓	✓	✓
MH-SH12-01	The system shall be adaptable for future use in other markets or create the bases of other applications	✓	✓	✓
MH-SH12-02	The design process shall be documented	✓	✓	✓
MH-SH12-03	The project shall be executed within schedule	✓	✓	✓
MH-SH12-04	The project shall be executed within cost budget	✓	✗	✗
MH-SH13-01	The system shall be safe to manufacture	✓	✓	✓
MH-SH14-02	The system shall not burden the local or global ecosystem	✓	✓	✓
MH-SH14-03	The system shall not deregulate social control and order	✓	✓	✓
MH-SH14-04	The system shall positively impact public opinion	✓	✓	✓
MH-SH14-05	The system shall provide real-time progress information	✓	✓	✓
MH-SYS-01	[KEY] The system shall consist of at least one unmanned aerial vehicle	✓	✓	✓
MH-SYS-02	[KEY] The system shall be able to locate at least one lost person	✓	✓	✓
MH-SYS-03	[KEY] The system shall be able to provide first aid help to at least three missing persons	✓	✓	✓
MH-SYS-04	[KIL] The system shall be able to deploy a first-aid kit within a radius of $0.3m$ from target location	$0.3m$	✓	✓
MH-SYS-05	The system shall include a mobile ground unit	✓	✓	✓
MH-SYS-06	The system shall be able to communicate with a mobile ground unit	✓	✓	✓
MH-SYS-07	[KEY] The system shall be portable by man on foot walking on the mountain	✓	✓	✓
MH-SYS-08-A	[KEY] The system shall be operable at sea-level ($0m$) to $5000m$ altitude bounded by a latitude range of $S35°$ to $N65°$ during cruise	$0m$ to $5000m$	$0m$ to $6500m$	✓
MH-SYS-08-B	[KEY] The system shall be operable at sea-level ($0m$) to $5000m$ altitude bounded by a latitude range of $S35°$ to $N65°$ during hovering	$0m$ to $5000m$	$0m$ to $6500m$	✓
MH-SYS-09	[KEY] The system shall be operable at temperatures ranging from $-40°C$ to $60°C$	$-40°C$ to $60°C$	$-40°C$ to $60°C$	✓
MH-SYS-10	[KEY] The system shall have an endurance of at least two hours	$2h$	$2h$ up to $6h$	✓

ID	Requirement	Desired output	Design output	
MH-SYS-11	The system shall be rechargeable or refuelable at the mobile ground unit	✓	✓	✓
MH-SYS-12	The system shall be able to take-off and land semi-autonomously	✓	✓(fully autonomous)	✓
MH-SYS-13	[KEY] The unmanned aerial vehicle shall have a span of no more than $1.5m$	$\leq 1.5m$	$1.5m$	✓
MH-SYS-14	[KEY] The system shall have a weight lower than $18kg$	$\leq 18kg$	$15kg$	✓
MH-SYS-15	[KIL] The system shall include detection systems that can locate missing persons	✓	✓	✓
MH-SYS-16	The system shall be able to detect a person from a distance of $75m$	$75m$	$241m$	✓
MH-SYS-17	The system shall be able to cover an area of 6.9 km^2 in one hour	6.9 km^2	34 km^2	✓
MH-SYS-18	The system shall be available for operations within 15 minutes from ground transport mode	$15min$	✓	✓
MH-SYS-19	[DRV] The system shall be able to withstand winds of up to $80kmh^{-1}$	$80kmh^{-1}$	TBD	✓
MH-SYS-20	[DRV] The system shall be able to withstand gusts of up to $100kmh^{-1}$	$100kmh^{-1}$	TBD	✓
MH-SYS-24	The system shall be able to fly from one point to another autonomously	✓	✓	✓
MH-SYS-25	The system shall be able to return to the operator autonomously	✓	✓	✓
MH-SYS-26	The operator shall not lose contact under nominal operating conditions	✓	✓	✓
MH-SYS-27	[KIL] The system shall have a communication range of $50km$	$50km$	Global (satellite)	✓
MH-SYS-29	[KIL] The system shall be able to loiter in a given area	✓	✓	✓
MH-SYS-30	[KIL] The system shall be able to search a given path	✓	✓	✓
MH-SYS-31	[KIL] The system shall be able to search a given area	✓	✓	✓
MH-SYS-32	[KIL] The system shall be able to focus on a given point	✓	✓	✓
MH-SYS-33	The system shall have a communication loss mode	✓	✓	✓
MH-SYS-34	The system shall provide its location to the SAR-team in real-time	✓	✓	✓
MH-SYS-35	[DRV] The system shall have a real-time video link with a mobile ground unit	✓	Within line of sight, up to $3km$	✓
MH-SYS-36	The system shall store measured data of the operations	✓	up to $128GB$	✓
MH-SYS-37	The system shall be able to return to ground station without connection	✓	✓	✓
MH-SYS-38	The system purchasing cost shall not exceed €15,000	€15,000	€25,000	✗
MH-SYS-39	[KEY] The operational cost shall not exceed €$5/hour$	€$5h^{-1}$	€$52.5h^{-1}$	✗
MH-SYS-40	The life cycle cost shall not exceed €35,000	€35,000	€100,600	✗

ID	Requirement	Desired output	Design output	
MH-SYS-41	The system shall be available from the year 2018 onwards	2018	2016	✓
MH-SYS-42	The project shall be performed within development budget of €3,500	€3,500	> €12,500	✗
MH-SYS-43	The project shall be performed within manufacturing budget of €11,000	€11,000	€12,800	✗
MH-SYS-ELE-COM-01	The communication band shall be licensed	✓	✓	✓
MH-SYS-ELE-COM-02	The communication subsystem shall be able to transmit and receive a VHF band	✓	✓	✓
MH-SYS-ELE-COM-03	[KIL] The data rate shall be at least $7.5Mbps$	$\geq 7.5Mbps$	$13.6Mbps$	✓
MH-SYS-ELE-COM-04	The communication subsystem shall not exceed an average power consumption of $30W$	$\leq 30W$	$9W$	✓
MH-SYS-ELE-COM-05	The communication subsystem shall not exceed a maximum power consumption of $60W$	$\leq 60W$	$11W$	✓
MH-SYS-ELE-COM-06	The communication subsystem shall have a mass of less than $1kg$	$<1kg$	$0.581kg$	✓
MH-SYS-ELE-SNS-01	The sensing subsystem shall be able to record video with a resolution of at least 640 x $480pixels$	640 x $480pixels$	640 x $480pixels$	✓
MH-SYS-ELE-SNS-02	The sensing subsystem shall not exceed an average power consumption of $25W$	$25W$	$10W$	✓
MH-SYS-ELE-SNS-03	The sensing subsystem shall not exceed a maximum power consumption of $80W$	$80W$	$10W$	✓
MH-SYS-ELE-SNS-04	The sensing subsystem shall have a mass of less than $8kg$	$8kg$	$0.724kg$	✓
MH-SYS-ELE-SNS-05	The sensing subsystem shall be able to determine the location of the missing person with an accuracy of $5m$	$5m$	$3m$	✓
MH-SYS-ELE-DAT-01	[KEY] The data handling subsystem shall store its measured data for $120minutes$	$120min$	$240min$	✓
MH-SYS-ELE-DAT-02	The data handling subsystem shall have a storage capability of $128GB$	$128GB$	$128GB$	✓
MH-SYS-ELE-DAT-05	The data handling subsystem shall not exceed an average power consumption of $4W$	$4W$	$10.15W$	✗
MH-SYS-ELE-DAT-06	The data handling subsystem shall not exceed a maximum power consumption of $10W$	$10W$	$12.1W$	✗
MH-SYS-ELE-DAT-07	The data handling subsystem shall have a mass of less than $0.5kg$	$0.5kg$	$0.291kg$	✓
MH-SYS-ELE-NAV-01	The navigation subsystem shall be able to determine the location of the UAV with an accuracy of at least $3.5m$	$3.5m$	$3m$	✓

ID	Requirement	Desired output	Design output	
MH-SYS-ELE-NAV-02	The navigation subsystem shall determine the location of the UAV with a frequency of at least $3Hz$	$3Hz$	$10Hz$	✓
MH-SYS-ELE-NAV-03	The navigation subsystem shall allow for navigating to a location with a maximum allowable error of $3.5m$	$3.5m$	$3m$	✓
MH-SYS-ELE-NAV-04	The navigation subsystem shall provide the location of the UAV in Longitude GPS coordinates	✓	✓	✓
MH-SYS-ELE-NAV-05	The navigation subsystem shall allow the device to follow a predetermined track	✓	✓	✓
MH-SYS-ELE-NAV-06	The navigation subsystem shall not exceed an average power consumption of $6W$	$6W$	$3W$	✓
MH-SYS-ELE-NAV-07	The navigation subsystem shall not exceed a maximum power consumption of $10W$	$10W$	$3W$	✓
MH-SYS-ELE-NAV-08	The navigation subsystem shall have a mass of less than $0.5kg$	$0.5kg$	$0.03kg$	✓
MH-SYS-FPP-PROP-01	The propulsion subsystem shall allow for flight speeds of at least $12.5ms^{-1}$	$12.5ms^{-1}$	$0-78ms^{-1}$	✓
MH-SYS-FPP-PROP-02	The propulsion subsystem shall allow for VTOL or STOL operations	✓	✓	✓
MH-SYS-FPP-AERO-01	The system shall have a maximum speed of $40ms^{-1}$	$40ms^{-1}$	$78ms^{-1}$	✓
MH-SYS-FPP-AERO-02	The system shall have a turn radius of $32m$ at maximum speed	$32m$	$23m$	✓
MH-SYS-FPP-AERO-03	The system shall have a turn radius of $10m$ at stall speed	$10m$	$0m$	✓
MH-SYS-SAM-STR-01	[KEY] The vehicle mass shall consist of bio-based, re-usable or recyclable materials for at least 70% of mass	70%	95.3%	✓
MH-SYS-SAM-STR-02	The structure shall provide room for a first aid kit with a size of $0.32m$ by $0.23m$ by $0.15m$	$0.32m$ x $0.23m$ x $0.15m$	$0.32m$ x $0.23m$ x $0.15m$	✓
MH-SYS-SAM-STR-03	The structure shall withstand a load factor of 4 x g_0	4 x g_0	12 x g_0	✓
MH-SYS-OPS-FA-01	[KIL] The first-aid subsystem shall deploy a first-aid kit with an accuracy of $0.3m$	$0.3m$	✓	✓
MH-SYS-OPS-FA-02	The first-aid subsystem shall deploy a first-aid kit with a mass of $2kg$	$2kg$	$3kg$	✓
MH-SYS-OPS-CTRL-01	The control subsystem shall allow the vehicle to return to the mobile ground unit autonomously in case of a connection loss	✓	✓	✓
MH-SYS-OPS-CTRL-02	The control subsystem shall allow the vehicle to remain at a distance of at least $20m$ from objects	✓	✓	✓
MH-SYS-OPS-CTRL-03	The control subsystem shall allow for strategy input by the mobile ground unit	✓	✓	✓
MH-SYS-OPS-CTRL-04	The control subsystem shall allow the vehicle to be stable	✓	✓	✓

ID	Requirement	Desired output	Design output	
MH-SYS-OPS-TRA-01	The system shall be portable on the back of a person	✓	✓	✓
MH-SYS-OPS-TRA-02	The system shall have a weight less than $18kg$	$\leq 18kg$	$15kg$	✓
MH-SYS-OPS-TRA-03	The system shall be able to be disassembled	✓	✓	✓
MH-SYS-OPS-TRA-04	The system shall be able to be packed in under $15min$	✓	✓	✓
MH-SYS-OPS-TRA-05	The system shall be able to be deployed in under $10min$	✓	✓	✓
MH-SUS-01	[KEY] At least 70% of the structure shall be bio-based, re-used or recycled at the end of the aircraft service-life	70%	95.3%	✓
MH-SUS-02	The system shall not exceed 50% of the emissions of a helicopter flying during the same time	✓	✓	✓
MH-SUS-03	The system shall not exceed a sound pressure level of $50dB$ in a $10m$ radius from launch site	$50dB$	$76dB$	✗
MH-SUS-04	The system shall not exceed a sound pressure level of $65dB$ on ground during search operations	$65dB$	$59dB$	✓
MH-SUS-06	The system shall on average have a repair time of maximum $120minutes$	✓	✓	✓
MH-SUS-07	The system shall have spare parts available separately	✓	✓	✓
MH-SUS-09	At least 70% of the waste during production should be biodegradable or recyclable	70%	✓	✓

10.5.2 Explanation Unmet Requirements

Some of the requirements set in the *Midterm Report* [3] were not met. This section gives an explanation on those requirements.

- **MH-SH8-02: The system shall comply with national and international law in the area of operation** In current regulations the UAV has to perform its mission within line of sight. In mountain rescue application this is not desirable. However, the regulations are currently under discussion and will be changed in near future. It is believed that, especially for life saving applications, the regulations can be changed in favour of *Nora*.

- **MH-SH12-04: The project shall be executed within cost budget** Found in the items below, the purchase price could not be kept at predefined level, neither could the costs for production.

- **MH-SYS-38: The system purchasing cost shall not exceed €15,000.** The system purchasing cost was established to be €25,000, mainly due to advanced yet costly imaging hardware. Even though this value his significantly higher than anticipated, it was found that it was still allowable for the intended market.

- **MH-SYS-39: The operational cost shall not exceed €$5h^{-1}$** The operational cost turned out to be €52.5 value, which is basically due to a much longer lifetime than expected and thus naturally the sum of operational costs is higher. The initial estimation was simply too low and the actual costs are still significantly less than that of a helicopter.

- **MH-SYS-42: The project shall be performed within development budget of €$3,500$** Initially thought of any costs that had to be taken during actual designing, the eventual development budget requirement could not be complied to. Successfully developing *Nora* would also include thorough testing with prototype(s) and thus costs easily exceed €$12,500$.
- **MH-SYS-43: The project shall be performed within manufacturing budget of €$11,000$** Manufacturing costs of a single unit was not kept within the requirement partially due to high costs for imaging detection, like MH-SYS-38.
- **MH-SYS-ELE-DAT-05: The data handling subsystem shall not exceed an average power consumption of $4W$.** The data handling subsystem uses $10.15W$ on average. However, enough power is generated to accommodate for this extra required power.
- **MH-SYS-ELE-DAT-06: The data handling subsystem shall not exceed a maximum power consumption of $10W$.** The data handling uses $12.1W$, which is just above budget, but again enough power is present to deliver $12.1W$.
- **MH-SUS-03: The system shall not exceed a sound pressure level of $50dB$ in a $10m$ radius from launch site.** A sound pressure level of $76dB$ was established.

10.5.3 Project Guide Requirement Compliance

In Table 10.8 the requirements as outlined in the DSE *Project Guide* are checked for compliance.

Table 10.8: Project Description Requirement Compliance

Requirement	**Desired output**	**Design output**	
System shall consist of aerial device for support of ground rescue teams	✓	✓	✓
Device shall search for and offer first aid help to a group of 3 mountaineers	✓	✓	✓
Device shall be portable by man on foot walking on the mountain	✓	✓	✓
Device shall take-off and land with minimal human help	✓	✓	✓
Device shall be able to deploy 2kg first aid kit for high altitude with precision	✓	✓	✓
Device shall be able to operate at altitude up to and including $5,000m$	$5,000m$	$6,500m$	✓
Device shall have a maximum wing span of $1.5m$	$1.5m$	$1.5m$	✓
Operating cost shall be maximum half of the cost of a helicopter flying during the same time	€$1650h^{-1}$	€$52.5h^{-1}$	✓
At least 70% of the structure shall be biobased, re-used or recycled at the end of the aircraft service-life	70%	93.5%	✓
Device shall have an endurance of $2h$.	$2h$	$2-6h$	✓
Device can be re-charged at ground support	✓	✓	✓
Device shall operate under normal weather conditions when ground support can go out with the device	✓	✓	✓

10.6 Risk Management

In this section, the technical risks of the final design are identified, assessed, analysed and handled. Both development (related to the design process) and operational risks (related to the actual operation) were assessed during the project.

The development risks, shown in the *Midterm Report* [3], were used to make decisions on the final design. Summarised, these were the consequence and probability estimations that the predefined requirements would be met. These risks will not be discussed in this section, because an elaboration on the compliance of the requirements will be shown in Section 10.5.

The possible operational risks of the mission and the subsystems, will be identified in Subsection 10.6.1. The identification process is followed by the assessment of these risks shown in Subsection 10.6.2 using a risk map. Finally, the risks are analysed and handled with mitigation and minimisation techniques, described in Subsection 10.6.3.

10.6.1 Risk Identification

Risk identification is the anticipation and recognition of potential risks. These risks will be identified for the mission and the different subsystems.

Mission: Risks related to the general mission and operation of the UAV.

1	Ground unit unable to assemble and deploy UAV.
2	Ground unit unable to carry UAV due to size.
3	Ground unit unable to carry UAV due to weight.
4	UAV unable to take-off in certain environment.
5	UAV unable to land in certain environment.
6	Extreme weather conditions.
7	First-aid package drop fails.
8	UAV enters a prohibited area.

Structures, Materials & Manufacturing: Risks related to the structures (STR), materials (MAT) and manufacturing (MNF) of the UAV and package.

20	Structural failure of UAV components due to loads.	STR
21	Structural failure of package due to loads.	STR
22	Design/manufacturing weight addition.	STR
23	Non-optimal structural design.	STR
24	Connection structure failure.	STR
25	In-flight loading factor exceedance.	STR
26	Flutter resonance during flight.	STR
27	Temperature influence on structural characteristics.	STR
28	Fatigue.	MAT
29	Material imperfections.	MAT
30	Moisture, corrosion, degradation.	MAT
31	Plastic deformation/creep.	MAT
32	Non-optimal material selection.	MAT
33	Manufacturing tolerances.	MNF

Flight Performance & Propulsion: Risks related to the aerodynamics (AERO), propulsion (PROP), power (PWR) and stability & control (CTRL) of the UAV.

40	Inaccurate CFD results.	AERO
41	Unstable stall behaviour.	AERO
42	Not enough lift generation.	AERO
43	Too much drag generation.	AERO
44	Electric engine failure. (rear)	PROP
45	Electric engine failure. (hover)	PROP
46	Propeller blocked. (rear)	PROP
47	Rotor blocked. (hover)	PROP
48	Fuel system failure.	PWR
49	Accumulator system failure.	PWR
50	Combustion engine failure.	PWR
51	Generator failure.	PWR
52	Accumulator capacity reduction due to temperature.	PWR
53	Fuel Frozen.	PWR
54	Unstable aircraft.	CTRL
55	Unsuccessful transition hover to horizontal at same altitude.	CTRL
56	Failure of control surface.	CTRL

Electronics: Risks related to the navigation (NAV), detection (DET), electrics (ELE) and telecommunication (TELE) of *Nora* and package.

60	UAV unable to autonomously return to ground unit.	NAV
61	UAV unable to detect missing person due to person movement.	DET
62	Thermal camera failure.	DET
63	Optical camera failure.	DET
64	Thermal camera software failure.	DET
65	Optical camera software failure.	DET
66	Camera pointing system failure.	DET
67	Thermal camera lens zoom system failure.	DET
68	Acoustic sensor failure.	DET
69	Acoustic system unable to distinguish noise from desired signal.	DET
70	Conflicting detection systems.	DET
71	Electric failure due to environmental temperature.	ELE
72	Electric failure due to operating temperature.	ELE
73	Short circuit due to leakage.	ELE
74	Failure of GPS.	NAV
75	Temporarily lost data link during cruise.	COM
76	Permanently lost data link during cruise.	COM
77	Inaccurate maps resulting in mountain collision.	NAV

10.6.2 Risk Assessment

Risk assessment is the characterization of the probability and consequence of technical risks, in form of risks maps. In this risk map, the probability of occurrence, plotted on one axis, and consequence of the risks, on the other axis, are both qualitatively estimated.

The probability of occurrence is a function of state of technology maturity. In order of increasing probability of occurrence, the categories go from not likely to very likely.

The seriousness of impact on performance is expressed as a consequence for the mission critically. The categories of the consequences in order of increasing severity of impact are:

- Negligible: inconvenience or nonoperational impact
- Marginal: Degradation of secondary mission or small reduction in technical performance
- Severe: Mission success is questionable or some reduction in technical performance
- Critical: Degradation of mission or reduction in technical performance
- Catastrophic: Mission failure or significant non-achievement of performance

The identified risks listed in section 10.6.1, are plotted in Table 10.9. The probability of occurrence and consequence of the risks are qualitatively estimated. The closer the risk is placed to the top-right, the higher the risk. In section 10.6.3, mitigation techniques to move the risks to the bottom left corner will be discussed.

10.6.3 Risk Analysis & Handling

In this section, the minimization and mitigation techniques for the risks, plotted in Table 10.9, are discussed. The objective is to spend scarce resources (people, money, time) in those areas where largest reduction in risk will be achieved for risk minimisation. The goal is to keep risks low and move the risk items to the lower left corner on the risk map through either a reduction in probability, consequence or both. The mitigation and minimization methods for the risks are given in Table 10.10.

Table 10.9: Risk Map

Catastrophic	20,24	1,56,71,73,77	61		
Critical	2,8,28,31,49,51 74	3,6,21,26,41, 42,62,66	7,64,72	40	
Severe	25,48,50	4,5,27,30,32, 33,43,44,46,53, 60,63,67,70, 76	22,65		
Marginal	29	45,47,68	23	54,69	
Negligible		55	52	75	
Consequence **Probability**	**Very unlikely**	**Unlikely**	**Moderate**	**Likely**	**Very likely**

Table 10.10: Risk Minimisation & Mitigation

#	**Minimization**	**Mitigation**
1	Improve modular connection systems.	Better training of the ground team.
2	Reduce size of UAV by improvements.	Design custom backpacks to fit UAV.
3	Reduce the weight of the design.	-
4	-	Search for a different take-off location.
5	-	Land in a remote location.
6	Obtain weather forecast information. Over design the UAV.	Fly at higher altitudes to avoid transient areas. Abort mission when control becomes difficult.
7	Make the design fail safe.	Rush the rescue team to the location
8	Obtain information about all prohibited airspaces in the area.	Turn around and leave the area.
20/21	Design for 12g with a 1.5 safety factor.	-
22	Use stronger materials. Over design structure	Apply strict management on manufacturing.
23	Maximise use of manufacturing tolerances.	-
24	Highly over-design the connection structure.	-
25	Analyze gust loading and add a safety factor.	Adapt the controller to fly safer.
26	Use damping mechanism.	Transition to hover mode to reduce the flutter.
27	Use materials that work under large temperature ranges.	-
28	Use more fatigue insensitive materials.	Regularly inspect vulnerable components.
29	Anticipate material imperfections during the design phase.	-
30	Use low corrosive materials.	Regularly inspect vulnerable components.

#	Minimization	Mitigation
31	Design for 12g with a 1.5 safety factor.	Replace deformed parts.
32	Consider as many materials as possible.	-
33	-	Apply strict management on manufacturing.
40	Use different CFD software programs.	Re-tune the controller.
41	Add stall preventing solutions.	-
42	Do an aerodynamic analysis.	Fly faster.
43	Separate wings as much as possible and over design the horizontal rotors.	-
44/46	-	Transition to hover mode.
45/47	-	Transition to cruise mode.
48/50/51	-	Immediately land UAV on batteries.
49	-	Immediately land UAV on the engine.
52	Design for limit temperatures.	Land if necessary.
54	Provide artificial stability.	-
55	Extensively test the controller.	Return to hover mode.
56	-	Transition to hover mode.
60	Use redundant location systems.	Land at another safe location.
61	Make swath width as high as possible.	-
62-65	-	Rely on other sensors.
66	-	Keep pointing in the same direction.
67/68	-	Rely on other sensors.
69	Implement other microphones to filter noise.	Rely on other sensors.
70	-	Recheck the location.
71/72	Design for limit temperatures.	-
73	-	Immediately shut down systems on that circuit.
74	-	Land safely.
75	More powerful communication devices.	Autopilot to fly autonomously without data link.
76	More powerful communication devices.	If possible fly back to launch position, otherwise land safely.
77	Add other anti-collision mechanisms.	-

10.7 Reliability, Availability, Maintainability & Safety

In the Midterm phase, the design characteristics for Reliability, Availability, Maintainability and Safety RAMS were analyzed [3]. The analysis is extended during the final design phase and can be found below. Subsection 10.7.1 introduces relevant terminology meanings whilst Subsection 10.7.2 deals with the concomitant preliminary analysis and quantification.

10.7.1 RAMS Terminology

In order to understand the analysis presented in Subsection 10.7.2, the RAMS terminology is elaborated upon individually below.

- **Reliability (R):** Probability that a system will perform satisfactorily under given operational circumstances that describe the mission over bounded time periods [44]. Often, it is also presented as a *Mean Time Between Failures* (MTBF) in hours [45] or the *Mean Time To Failure* (MTTF) in number of cycles [46].

- **Availability (A):** Degree that a system is ready and available for use as required, indicated as percentage of usage frequency [44]. Operational availability, as is of interest, is the probability that a system, when used under given conditions, will operate satisfactorily when called upon [46].

- **Maintainability (M):** Design characteristic pertaining to the ease, accuracy, safety and economy in the performance of maintenance functions [44]. Maintainability is the ability of the system to be maintained safely, at lowest possible cost and in the least amount of time [46].

- **Safety (S):** Degree that a system does not inflict injury, harm or danger to people, the environment or any other asset during the system's life cycle.[45] It is generally characterized by the freedom of hazards to humans and equipment [44].

10.7.2 RAMS Evaluation

Utilizing the RAMS characteristics presented in Subsection 10.7.1, a further theoretical analysis and, where possible, quantification of the individual factors are expanded below.

Reliability: The evaluation of any system in terms of reliability is based on defined concepts. Reliability of a system can be predicted through the use of the ubiquitous negative exponential survival function as presented in Equation 10.6, where t denotes the duration of an operational cycle in hours, and λ is the failure rate in per hour [45]. Note that the negative exponential uses a constant failure rate, such that it only makes sense to use this probability distribution on a system wide scale where failures can be modeled as random.

$$R(t) = e^{-\lambda t} \quad (10.6) \qquad\qquad Product(fail) = mVb \quad (10.7)$$

With a minimum mission duration of two hours, see Chapter 5 MH-SH2-08, the sole unknown is the failure rate. Using the method presented in [45], Equation 10.7 indicates the probability of human danger as a result of a catastrophic UAV failure as the multiplication of the aircraft momentum with its swath width, where m signifies mass, V the velocity and b the maximum span. The $Product(fail)$ presented in 10.7 is then compared with that of an airliner (Boeing 767) and its own failure rate.

The standard UAV parameters are taken, such as an expected mass of $15kg$, an average velocity of $30m/s$ and a maximum span of $1.5m$, which amounts to a $Product(fail) = 675$. For a Boeing 767, this number equals $Product_{Boeing} = 2.8 \cdot 10^8$ for a $\lambda_{Boeing} = 1 \cdot 10^{-10}$ [45]. Assuming further that the UAV will fly in non-populated areas which amounts to a reduction factor of 10^{-3}, the UAV failure rate is $\lambda = 0.04$. Combining the mentioned failure rates λ and the average mission duration with Equation 10.6 yields a reliability of $R = 92\%$.

For helicopter structural components the reliability must be 99.9999%, also known as the six nines [47]. The difference between 99.9999% and 92% can be explained by the fact that 99.9999% is only for one structural component. Combining multiple components in series already lowers the reliability. Next to that also other components are taken into account within the 92%, such as the sensor systems, the communication system, the hard- and software components. Therefore 92% is already quite good, especially taking into account that *Nora* has not yet been tested which will greatly increase the reliability.

Availability: Inherent availability, which is of interest, is the probability that a system, when used under mission conditions in an ideal support environment will operate satisfactorily at any time as required [46]. As such, it relates the *Mean Time Between Failures* (MTBF) with the *Mean Time To Repair* (MTTR), which in turn is also known as the *Mean Corrective Maintenance Time* (MCMT).

As detailed in [48], the MTBF is simply the reciprocal of the failure rate found previously, as denoted in Equation 10.8. The MTBF is found to equal 24.1 operational hours per failure.

$$MTBF = \frac{1}{\lambda} \quad (10.8) \qquad\qquad A(t) = \frac{MTBF}{MTBF + MTTR} \quad (10.9)$$

Using then Chapter's 5 MH-SUS-08 requirement, detailing a mean time to repair (MTTR) of two hours, the inherent availability is found through the use of Equation 10.9 [48]. The average rate of inherent availability equates to $A = 92\%$.

Maintainability: Maintainability is key for the success of *Nora*. Most importantly, proper maintainability of the system will ensure *Nora* will be maximally available for SAR missions. Moreover, good maintainability ensures a more sustainable design as smaller parts of the system need to be replaced if a repair is necessary. In the *Midterm Report* [3], some key points of focus were listed to guarantee good maintainability. In the enumeration below its is explained how these points served as a guideline to ensure good maintainability of *Nora*.

1. **Separability:** In the entire design philosophy of *Nora*, both separability and modularity have been key considerations. The primary reason for separability was easy and flexible operation. But it also means that the UAV is very well maintainable. The separable structural components make it easy to replace or maintain outer parts of the structure without the risk of damaging other parts.

2. **Modularity and Access Points:** Besides the external structure, the internal subsystems are also very accessible due to *Nora*'s modularity. Since sensors can be replaced or exchanged depending on the type of operation, the fuselage has a high number of access points. An overview of these access points is given in Figure . These access points are shut with a hinged lid to avoid parts being dropped, damaged lost or misplaced when sealing the system. The separability and modularity combined can significantly lower the amount of time required to reach the relevant part and thus can also usually reduce labor cost.

3. **Sealings & Coatings:** *Nora*'s foam surfaces are treated with foilcoating Ultracote to make the outside weather resistant. Since this material is widely applied in remotely controlled model aircraft, applying and repairing the material can be done by the operator.

4. **Tools Required:** Since *Nora* is designed to be assembled and dismantled during operation, stripping her of the part to be repaired only requires simple tools such as a screw driver. The actual maintenance on complicated subsystems, such as the camera system or the engine require more specialized tools and, more importantly, knowledge. Besides, the main structure is primarily constructed out of carbon fibre reinforced plastic due to lightweight design, which takes skill and practice as well.

For the purpose of software maintenance, the enumeration below can be used in the design towards proper maintainability.[46]

1. **Modular Programming:** Use of definitions and separate code units increases ease of adaptations. Furthermore, the use of an online repository with a revision control system such as Github or Bitbucket, significantly reduces the probability of conflicted copies.

2. **Code Consistency:** Use of consistent naming conventions facilitates software adaptations, especially when working on the software with multiple people.

3. **Application Updates:** The SAR teams using *Nora* will mainly interact with the UAV via their tablets or computers connected to its online connection application. Software updates will thus be easily implemented through the relevant "App Store", and will keep *Nora* up to date at all times. The SAR teams will simply have to download the updates and the UAV will be ready to go.

Safety: Safety, as defined by *Oxford Dictionary*, is the condition of being protected from or unlikely to cause danger, risk or injury. In the case of a SAR UAV, safety is categorized to apply to three divisions, namely ground based SAR team, missing persons as well as environmental safety. Ground and missing person safety are related to for instance take off and landing capabilities and package delivery methods. Environmental safety relates for instance material recyclability as well as power source pollution as detailed in Chapter 10.9. Safety, other than risk, tries to encapsulate the consequence of situations, rather a combination of consequence and probability [46]. However, a large portion of risk mitigation plans that focus on reducing situational consequence, are beneficial for safety too.

Fatigue: The fatigue life of *Nora* is estimated based on a preliminary method as outlined in [41]; please refer to Equation 10.10. L_{10} signifies the amount of meter flight per gust having a velocity greater than $3.05m/s$, taken from reference as $5000m$. K_1 and K_n are fudge factors set at 2.97 and 1.43 respectively as detailed in [41]. σ is set as the fracture stress of the carbon fibre monocoque in MPa at 49. C is another fudge factor implemented by [41] and equals 1000. Lastly, V_e is set as a velocity of $40m/s$ or $144km/h$.

$$D_{Total} = D_g R_{avg} + D_{extra} \qquad D_g = \frac{46.55}{2L_{10}} \left(\frac{K_n}{C}\right)^2 \left(\frac{K_1 V_e}{\sigma}\right)^{5.26} \quad (10.10)$$

An additional D_{extra} factor of $0.1D_g$ as in [41] and a $R_{avg} = 288km$ based on a two hour mission at $40m/s$ are implemented. Finally, using Equation 10.11, the number of flights until failure through fatigue is computed as roughly 1000. Assuming an average one rescue sortie per day, this equates to roughly five years of operational life.

$$N_{fail} = \frac{1}{3} \frac{1}{D_{Total}} \quad (10.11)$$

A similar approach for the foam of the structure yields an operational life of 100 flights until fatigue failure. Assuming the same sortie frequency, this would mean the foam structure needs to be replaced every three months. The titanium connectors, as outlined in Subsection 9.6.11, have a flight number till fatigue failure of $\pm 4.5 \cdot 10^6$ according to the above analysis. Hence, the titanium structure can be deemed to survive the entire life of *Nora*.

10.8 Investment Analysis

Knowledge on financial situations, both of current phases as well as future planning, is of paramount importance. Although the expected scope of cost is quite complex to establish, insight in the different types of costs is essential for a start. For this very reason, a cost breakdown diagram has been constructed. Not only to indicate different sorts of expenses as said before, but more importantly to individually assign costs to the identified expenses more accurately and thus give a better indication of the possible return on investment. Its computation is the main goal of this section; to develop notion, as best as possible at this point in time, of the profit that can be made on the project of *Nora* as a function of sales and costs. The remainder of this section sets out to address those sales and costs. Firstly, the costs are explained and estimated. Followed by an elaboration on the market price and resulting break-even point. Finally, the return on investment will be given.

10.8.1 Cost estimations

In this section, an overview is given of the different cost estimations. A cost breakdown diagram, shown in Figure 10.4, is used to identify the different costs. The research and development, production, operational and financing costs are elaborated below.

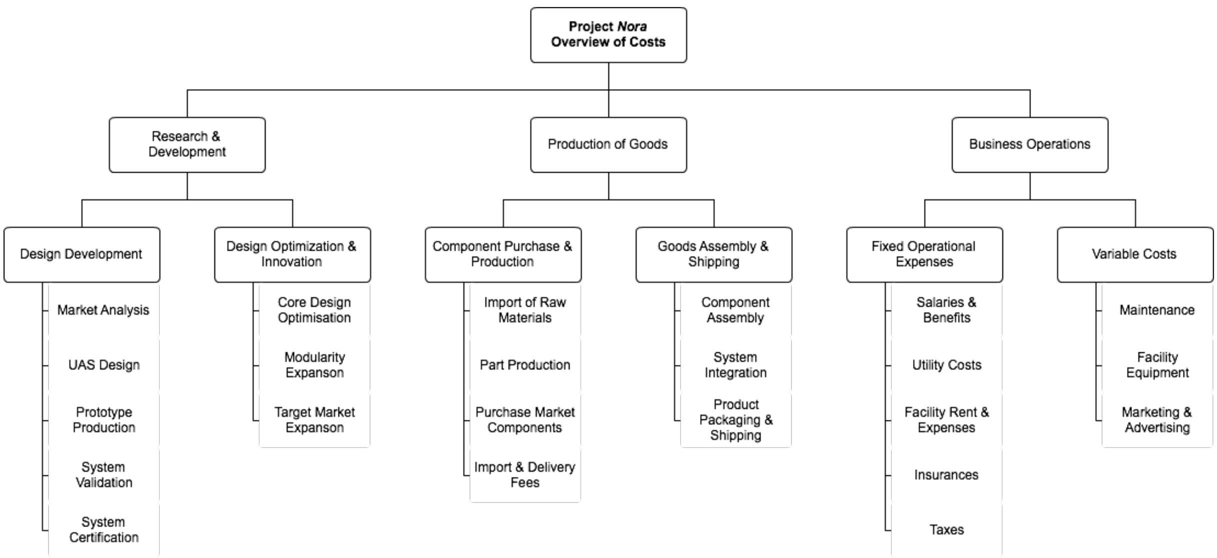


Figure 10.4: Cost Breakdown Diagram

Research & Development Costs

The first form of costs are categorised as development cost and are made during the design phases first. In early stages, the main expense is the many hours of the engineers put into the literature studies, market analysis and design of concepts. These are not stated as costs for Research & Development directly, since they find their way via operational costs. A first estimation for investment up to the maiden flight of *Nora* may be established by considering systems tests, construction of prototype and certification procedures.

Apart from initial development, the enterprise will most likely accommodate a research and development department for design improvement, optimisation and innovation on modularity and separability systems. Budgets are assumed to be assigned annually to this department. Not only may it simply improve the original product, research facilities ensure profits are reinvested and allow for an increase in continued growth. [1]

Production Costs
Production costs may roughly be defined as the expenses that have to be made to produce a single unit of goods. [2] In Table 10.1, the total of prices of *Nora*'s components may be found. Assembly, packaging and shipping of the finalised product form the value adding processes. Assembly costs are presumed to reduce over the years due to more sophisticated means of production and assembly.

Business Operating Costs
Investment into *Nora* is subject to those costs made for the development and production of *Nora* and related products and yet cannot be related to one unit of product specifically. Such costs are defined as operational costs and may be categorised as either fixed, or frequently returning costs and variable costs.

Fixed costs are costs that have to be made every week, month or year for the business to remain operational. These are, amongst others, salaries and benefits for employees, costs for using electricity and water, insurance payment and taxes. Since their presence is a given, they can easily be accounted for. Variable costs have, in contrast to fixed costs, an uncertainty in appearance and magnitude. Variable costs may be thought of as equipment replacement, maintenance of production facilities, but also more deterministic aspects such as marketing and advertisement. At this moment, variable costs are expected to be higher during the business start-up and gradually decrease once facility needs are more satisfied.

Financing Cost
Although not necessary for production and market introduction of *Nora*, an efficient capital structure can significantly increase the viability and investment return of the project. Equity input from angel investors can best be supplemented with additional debt financing from either a bank, in the form of bonds to fixed income investors or from Peer-to-Peer loans.[3] The optimal capital structure would entail a non-amortising lump sum upfront, paying the interest accrued over the years and finally paying off the loan in bullet form at the end of the lending period. Please refer to Subsection 10.8.3 for insights into the effects of this financing method.

10.8.2 Market Price

The market price of *Nora* is established on €25,000. This price was based on the motivation to reach the break-even point (BEP) in 5 years, taking the costs described in the previous section into account. These costs are estimated in Table 10.11 in the next subsection. Using the market volume estimation described in Section 4.3, it is determined that the BEP will be reached at the end of 2020 when 123 Noras will be sold. From competition, described in Section 4.1, it can be seen that this price is relatively low compared to UAVs with similar functions. This low price was chosen, based on the company's philosophy to reach a bigger target group where even smaller organisations will be able to afford *Nora*. The price is however subject to change in order to reflect the market demand for *Nora* if deemed feasible.

10.8.3 Return on Investment

To predict total return, post initial investment analysis has been done on the possible revenue and the cost that must be made to realise that same revenue. From the found revenue and cost resulting from

[1] Research and Development Expenses, URL `http://www.investopedia.com/terms/r/research-and-development-expenses.asp`
[2] Cost of Production, URL `http://www.businessdictionary.com/definition/cost-of-production.html`
[3] Peer-to-Peer Lending `www.lendingclub.com` [cited 24 June 2015]

the *Nora* project, a profit analysis was conducted. This is formally defined as a return on investment analysis and put in mathematical terms can be defined as Equation 10.12.

$$RoI = \frac{Revenues - Investments}{Investments} \cdot 100\% \tag{10.12}$$

All types of costs clarified in the previous part, have been stated and quantified in the overview given in Table 10.11 and form the capital invested into the project. The values between brackets in this table are negative values. The result, defined as Revenues, forms the primary source of income for the *Nora* project. Please refer to Figure 10.5 for the required capital structure for the yearly profit margin and total cost respectively. The interest rate accrued was taken as variable over the loan ranging from 2.5% for a loan of €500,000 to 15% for one of €3,500,000. [4] A €1,500,000 loan, which would bring the debt-equity ratio to 15%, was found optimal and would bring the yearly estimated return up to roughly 5.2% and over a seven year period up to roughly 42%. Please refer to Figure 10.5. For the preliminary investment analysis, the calculations were based on a loan of €1,500,000 in the first year which will be fully paid back after 7 years. With this loan the cash will always stay positive, with the lowest cash flow value of €7,385 noted in year 2018. This is deemed an optimal cash account structure. In the detailed design process, options as revolving credit lines or investments from business angels will be investigated to optimise the financing costs.

The 7-year return on investment, based on the estimated total costs of €10,435,000 and the total revenue of €14,850,000 as shown in Table 10.11. The total net profit will be €4,415,000 or 42%. See also Figure 10.5.

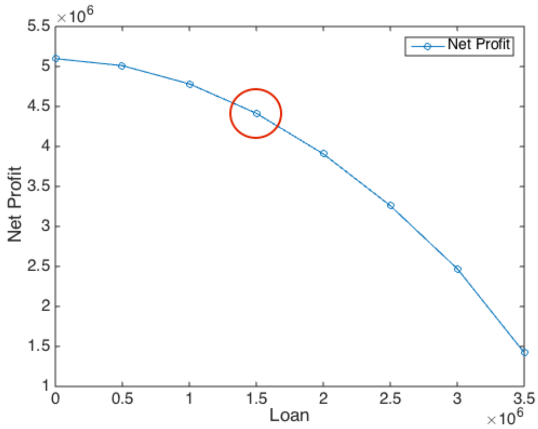


Figure 10.5: Net Profit Capital Structure Relationship

Table 10.11: Nora Cash Flow Statement

		2015	2016	2017	2018	2019	2020	2021	2022	Total
Units Produced	[Unit]	-	1	5	20	31	67	148	322	594
Price	[€/Unit]	-	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Revenues	**[1000€]**	**-**	**25**	**125**	**500**	**775**	**1,675**	**3,700**	**8,050**	**14,850**
Propulsion	[€/Unit]	-	470	470	470	470	470	470	470	3,290
Structures	[€/Unit]	-	3,335	3,335	3,335	3,335	3,335	3,335	3,335	23,345
Detection	[€/Unit]	-	7,363	7,363	7,363	7,363	7,363	7,363	7,363	51,542
Control	[€/Unit]	-	322	322	322	322	322	322	322	2,254
Communication	[€/Unit]	-	1,157	1,157	1,157	1,157	1,157	1,157	1,157	8,099
Assembling	[€/Unit]	-	85	85	85	85	85	85	85	595
Shipping	[€/Unit]	-	100	100	100	100	100	100	100	700
Bill of Materials	[€/Unit]	-	12,832	12,832	12,832	12,832	12,832	12,832	12,832	89,824
Production Cost	**[1000€]**	**-**	**(13)**	**(64)**	**(257)**	**(398)**	**(860)**	**(1,899)**	**(4,132)**	**(7,622)**
Salaries (10PPL)	[€]	-	180,936	184,555	188,246	192,011	195,851	199,768	203,763	1,345,130
Benefits (10PPL)	[€]	-	56,090	57,212	58,356	59,523	60,714	61,928	63,167	416,990
Office Rent	[€]	-	6,000	6,000	6,000	6,000	6,000	6,000	6,000	42,000
Office Expenses	[€]	-	3,600	3,600	7,200	7,200	7,200	7,200	7,200	43,200
Utilities	[€]	-	1,800	1,800	1,800	1,800	1,800	1,800	1,800	12,600
Communication	[€]	-	1,800	1,800	1,800	1,800	1,800	1,800	1,800	12,600
Marketing	[€]	-	500	600	700	800	1,000	1,500	2,000	7,100
Legal Expenses	[€]	800	1,000	1,000	1,000	1,000	1,000	1,000	1,000	7,800
Office Equipment	[€]	10,000	7,500	5,000	5,000	5,000	5,000	5,000	5,000	47,500
Operational Cost	**[1000€]**	**(11)**	**(259)**	**(262)**	**(270)**	**(275)**	**(280)**	**(286)**	**(292)**	**(1,935)**
Financing Cost	**[1000€]**	**1,500**	**(98)**	**(98)**	**(98)**	**(98)**	**(98)**	**(98)**	**(1,598)**	**(683)**
R&D Cost	**[1000€]**	**(50)**	**(35)**	**(30)**	**(25)**	**(20)**	**(15)**	**(10)**	**(10)**	**(195)**
Net Profit (Costs-Revenues)	**[1000€]**	**1,439**	**(380)**	**(329)**	**(150)**	**(16)**	**422**	**1,407**	**2,018**	**4,415**

[4] Peer-to-Peer Lending `www.lendingclub.com` [cited 24 June 2015]

10.9 Sustainability

Sustainability is a very important concept in design nowadays. In the past, waste was not really taken into account. The mindset was that the waste problem would be dealt with when it actually became a problem. Years later, the waste problem arose and people started thinking of ways to clean up this ever increasing problem, the so called "cleaning technology".[49]

Today, waste is produced at a faster rate than it can be cleaned. Therefore, awareness arose that instead of cleaning waste, the focus should lie on reducing the production of waste. So "cleaning technology" shifted, and is still shifting, towards "clean technology" [49], in other words: sustainable development. Sustainability is defined as a very broad concept and it contains two key components. The first of these is the concept of needs, in particular the essential needs of the world's poor. The second is the idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs. [50]

From this definition, it is clear that future needs are taken into account. Sustainability is therefore a long-term concept. It also emerges that sustainability is a very broad concept and can be applied to almost everything. Therefore sustainable development is often split into smaller aspects. One way to do this is with the three pillar approach. This approach splits sustainability into three aspects: the environment, the economy and the society. [51]

These three aspects influence each other and therefore they are considered to have an overlapping problem set. With the solution based on the problem, there is also a solution set, which also needs to be under multiple pillars. Finally, the three pillars must be in harmony to obtain sustainability. When all aspects of sustainability are taken into account, the future relevance of the system remains. In the following section each of these pillars will be addressed separately. However it should be noted that it all three pillars were taking into account simultaneously, yielding the best possible sustainable design when also taking into account the other system needs.

10.9.1 Environmental Sustainability

The environmental sustainability is the most evident aspect of a sustainable design. Sustainability is all about creating a clean product. In the environmental category this means minimising the energy used and the emissions of harmful gases inducing climate change. Moreover the structure should be biodegradable or recyclable to ensure it can be used after its life-cycle and the amount of material used should be minimized. These needs contradict with other system needs and therefore the environmental sustainability was constantly addressed during the design process. During the design process a constant trade-off was present between the sustainability and other design characteristics. In the Baseline Report [2], a set of requirements for the sustainability was made. These will are individually elaborated on below.

- **MH-SUS-02: The system shall not exceed 50% of the emissions of a helicopter flying during the same time.** In research it was found that a search and rescue helicopter of the NSW Emergency Services in Newcastle uses 300 litres of fuel per hour. This converts to 690 kg of CO_2 per hour, when the density of gasoline is used for fuel. *Nora* produces 1.4 kg of CO_2 per hour when in hover mode and 0.15 kg per hour in cruise mode. This means that even during hover mode, 0.2% of the emissions are produced by *Nora*. It is key to observe, that *Nora* does not replace the necessity of an helicopter when picking up individuals. It was found that helicopters are usually not used in the search phase of an operation and therefore more CO_2 may be produced during the the entire operation whilst still meeting the requirement. [5], [6]
- **MH-SUS-09: At least 70% of the waste during production should be bio-degradable or recyclable.** During the production of *Nora*, the largest waist will be produced during the cutting of the foam. Since foam is fully recyclable this will not induce any problems for the set requirement. The carbon fiber needs will hardly produce any waste as it uses resin transfer moulding for the fuselage and filament winding for the wing structure. The production of the landing gear is done using extrusion so waste is kept to a minimum as well. The exact recyclability of structural mass has been found to equal 93.5%.

[5]Rescue Helicopter, URL `http://www.rescuehelicopter.com.au/About/Operations`[cited 18 June 2015]
[6]Carbondioxide, URL `http://www.icbe.com/carbondatabase/volumeconverter.asp`[cited 18 June 2015]

10.9.2 Economical Sustainability

Besides being environmentally sustainable, *Nora* should have healthy financial management. This means that it should provide long term benefits. This is mostly achieved by making the system separable and modular. By doing so the market is expanded. The primary system has an endurance of 2 hours and is able to detect missing persons using a combination of thermal and optical imaging. However another set of wings will be developed for longer range applications. Furthermore multiple detection systems can be added and interchanged, which makes the system widely applicable and leaves the possibility of adding or solely using new technology when readily available, such as the noise detection system presented in Section 8.2.2. By doing so the system should be profitable over a longer period. Besides adjusting to the the rapidly changing technology, a modular system can be sold for more purposes than search and rescue in mountain application. Section 11.2 contains a more detailed description on the future financial plans of *Nora*. It should also be noted that *Nora* provides economic sustainability due to a reduction in operational costs for SAR missions. This reduction should positively influence society as a whole.

Furthermore two more sustainability requirements will be elaborated upon within in this section and can be found below.

- **MH-SUS-06: The system shall on average have a repair time of maximum** $20 minutes$**.** The reparation time of course highly depends on the component that is broken. However the open structure and the separability of the system make replacing components relatively easy, increasing the chances of meeting the requirement. The exact average reparation time will have to be verfied when *Nora* is on the market.
- **MH-SUS-07: The system shall have spare parts available separately.** Parts will be separately available, especially because a modular system is to be sold to which multiple extension packages can be bought.

10.9.3 Societal Sustainability

The last pillar in the three pillar approach is the societal sustainability. This means no harm should be done to a society or the people within it. This in case of technology means that the working conditions in foreign countries have to comply to certain standards. These are mainly regarding working hours and salary. Furthermore no harm should be done to the mountain inhabitants and other people present in the mountain terrain. This concerns physical harm due to *Nora* crashing, which will always remain a risk, but also noise pollution. The following two requirements concern the maximum allowable level of noise pollution set in the requirements.

- **MH-SUS-03: The system shall not exceed a sound pressure level of** $50dB$ **in a** $10m$ **radius from launch site.** In this stage it was not possible to perform a detailed noise analysis. Aeroacoustics is a complicated subject, especially for a non conventional design layout such as *Nora*. It was however found that the set requirements may be to optimistic since a sound pressure level of $50dB$ at $10m$ equals approximately loud speech, but exact numbers will have determined in a later stage. [7]
- **MH-SUS-04: The system shall not exceed a sound pressure level of** $65dB$ **on ground during search operations.** Again the exact numbers will have to be determined at a later stage, but meeting the requirement will be complicated.

[7]URL: `http://www.engineeringtoolbox.com/voice-level-d_938.html`, [cited on 27/05/15]

11 | Project Follow-Up

The preliminary design is finished, subsequently the following the design phases can be planned. This chapter starts with Section 11.1 on the future logic. Here all the post DSE phases are described and a global planning is shown. Then future developments are addressed in Section 11.2. Lastly the verification and validation steps and plans are discussed in Section 11.3.

11.1 Future Logic

In this Section the post-DSE phases and activities are outlined. In Subsection 11.1.1 is explained what every phase consist of. Then in Subsection 11.1.2 a planning is given for these phases.

11.1.1 Post DSE Phases

So far, only the main parts of Nora are designed. The detailed design falls out of scope of this Design Synthesis Exercise (DSE). After the DSE the detailed design phase would follow. Subsequently, the focus will shift to production and sales in the production phase and marketing & service phase. After the production phase the product is ready for sale. Throughout all the phases risk mitigation has to be performed. In Table 11.1, a time estimation per phase is given, based on the assumption that ten persons will work full-time. Full-time means 9 hours per day and five days per week, no holidays included. In the same table, the activities are specified. In Figure 11.1 the logic order of activities is shown.

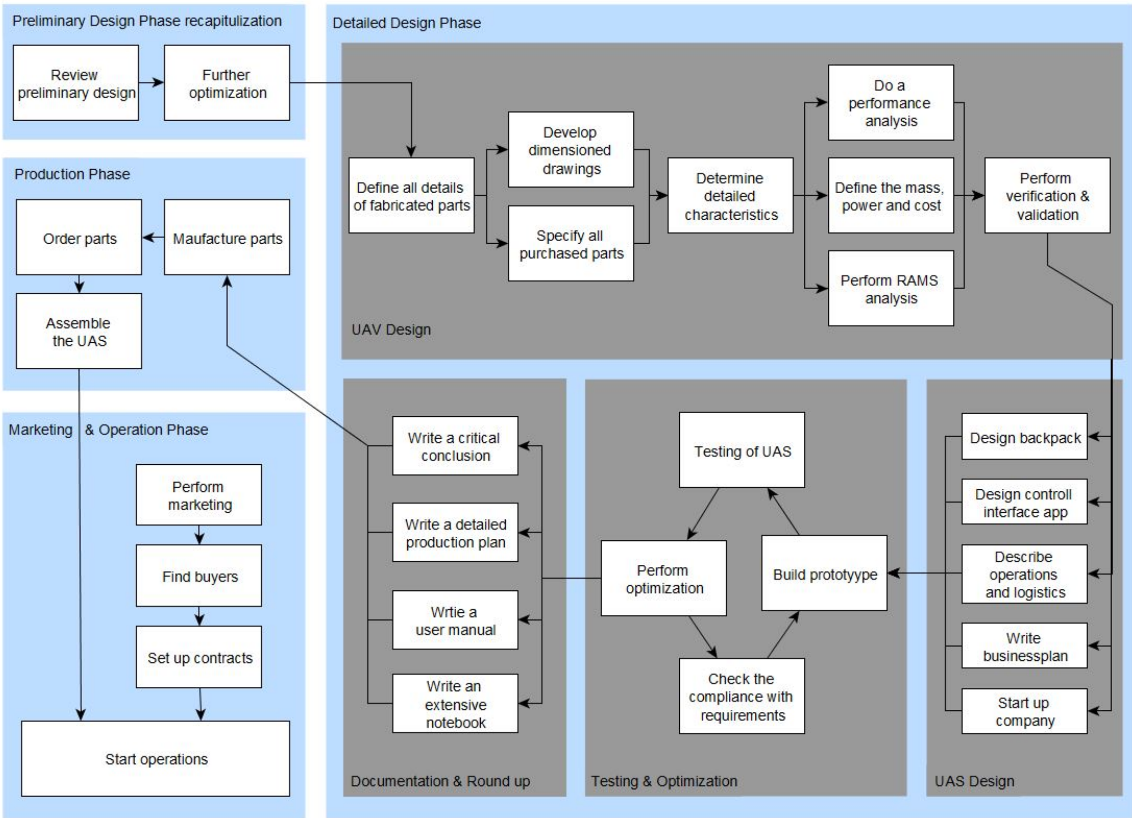


Figure 11.1: Block Diagram of Future Activities

Preliminary Design Phase recapitulization
In this phase the design (at this point) has to be reviewed. Then further optimisation of the major parts has to be performed before entering the detailed design phase-review of design.

Detailed Design Phase
In this phase every little detail has to be worked out, including design, testing and documentation. This phase consists of multiple sub-phases: the UAV design, the UAS design, testing & optimization, and

documentation & round up.[1]

UAV Design:
In this sub-phase every detail of all fabricated parts must be designed based on technical drawings. Besides, all purchased parts must be specified. Then the detailed characteristics of the UAV must be determined by means of a performance analysis and RAMS analysis. Furthermore, the total UAV mass, power needed and cost must be determined. Lastly the whole design method must be verified and validated.

UAS Design:
Next to the UAV, the UAS exists also of the backpack and the control interface app. These must be designed in this phase. Also the operations and logistics must be described in detail. Furthermore a company must be started up and a full business plan must be written outlining the economic opportunities. Also funds will have to be raised to be able to mamunfacture the prototype.

Testing & Optimization:
In this phase the product is extensively tested. To do so first a prototype must be build. Test results will be analyzed after which the UAS will be optimized. At this point there is a working design and the following sub-phase can be entered.

Documentation & round up:
This last sub-phase closes the design phase. Four things must be written: a critical conclusion about all aspects of the total design, a detailed production plan must be made, a user's manual (including safety procedures, troubleshooting, routine operating instructions and maintenance), and an extensive notebook which includes all pertinent information from bills to detailed drawings. Furthermore the UAS must get the right certifications.

Production
In the production phase Nora must be made. The parts that need to be purchased, must be ordered and the other parts must be manufactured. Then Nora must be assembled.

Marketing& Service Phase
Also the idea must be brought onto the market to find buyers. This is done in the marketing & service phase. When buyers are found contracts have to be set up. Finally Nora can start operating. In Table 11.1 no time is scheduled for this phase as this is a phase that is parallel to other phases and will continue (hopefully) for many years.

11.1.2 Planning

In the Gantt Chart in Figure 11.2 it can be seen when the activities start and how long they will continue. All the activities are marked red, the phases blue and the sub-phases in orange. After week 42 there is a ∞ sign. If an activity is until this ∞, it means this is an ongoing activity.

11.2 Future Developments & Modules

Although there are ideas and sketches for a tray system inside the fuselage of *Nora*, they need more calculations, with proper verification and validation. These trays will be designed with maintainability and modularity in mind, therefore one or two tray sizes will be developed with their own slot size. These slot sizes determine the inner width between the ducts. For every section with cutouts in the fuselage. Every slot will have its own USB type-C port, having a total of 16 slots for uniform connections. The proposed system shows a lot of resemblance with a hot swappable hard drive system as can be seen in Figure 11.3[2] that is often used in storage servers. With such a system it is possible to move the center of gravity by moving modules back and forward inside the fuselage. A bracket to fit the smallest tray form factor in the larger tray form factor will also be provided.

[1] Design Steps, URL `http://www.accudyne.com/our-process/installation-training-support-step-7-machine-technology-pr`, [cited June 16 2015]
[2] QNAP TS-879 Pro 10GbE Review, URL `http://www.storagereview.com/qnap_ts879_pro_10gbe_review`, [cited 24 June 2015]

Table 11.1: Duration & Activities per Phase

Phase	**Sub-phase**	**Duration** [weeks]	**Activities**
Preliminary Design Phase recapitulization		2	Review preliminary design Further optimization of preliminary design
	UAV Design	9	Define details fabricated parts Develop dimensioned drawings Specify all purchased parts Determine detailed char. Do a performance analysis Define mass, power & cost Perform RAMS analysis Perform verif. & validation
Detailed Design	UAS Design	11	Design backpack Design control interface app Describe operations & logistics Write business plan Start up company
	Testing & Optimization	17	Build prototype Testing of UAS Perform optimization Check the compliance with requirements
	Documentation & Round up	5	Write a critical conclusion Create detailed production plan Write user's manual Construct extensive notebook Get certifications
Production		8 -	Manufacture parts Order parts Assemble the UAS Perform marketing
Marketing & Operation			Find buyers Set up contracts Start operations
Total		**52**	

Figure 11.3: QNAP TS-879 Pro: an example with eight hot swappable hard drive bays. Received from Storage Review on 24 June 2015

In the future, the following modules can be further investigated which are considered beyond the scope of the project, but interesting for further developments. The proposed ideas for these modules are not restricted to the ones described below, as they will only indicate some of the most interesting modules. These modules will replace slots that are currently used in *Nora*.

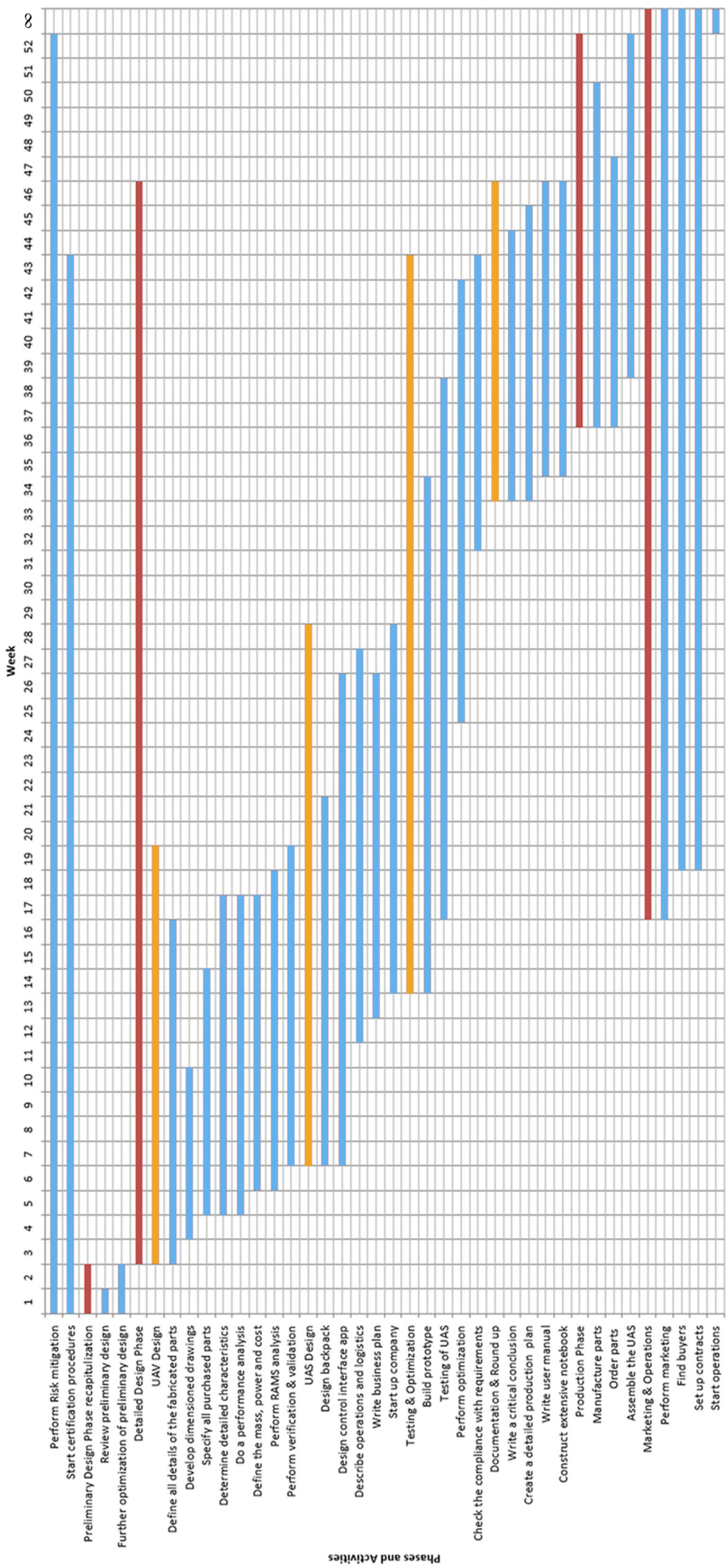


Figure 11.2: Gantt Chart of Future Phases

A module can be developed that is able to create high resolution height maps. Such a module further optimises flight paths, increasing operational effectiveness. Besides that it allows for better physical environment comprehension. This information can be used for a variety of applications, such as the identification of unsafe areas or research. Resolution of the resulting height maps will be higher than the $30m$ per height point currently available. Such a module can work with ultrasonic sensors or lasers.

An advanced camera system can be developed to improve the imaging performance. The focus for such a system may differ from our objectives. For instance, camera systems can be used that are larger, more expensive and/or have improved performance over *Nora*'s imaging system. Of course it is also possible to have a down-scaled variant, since visual cameras often touch the infrared spectrum as well.[3]

A high power lighting system could also be a module to assist ground units with a synthetic light source from the sky when natural light sources are unavailable. A larger and more capable and powerful sound system can also be implemented in a custom module. This provides the operator with a wider variety of sound signals. Including music, spoken messages and more decibels resulting in a larger range. For urban environment, the communication can be improved with the replacement of the satellite module with a cellular communication system. This will decrease the operational cost and increase the data rate. Besides that, communication systems with larger data rates (LTE up to $50Mbps$ upload speed [4]) and improved reliability are also an option.

To dramatically improve range, additional fuel tanks can be built-in. Additionally a battery module could also be implemented, either extending the range of full electric flight or replacing the fuel engine module to obtain the possibility to operate with zero emission flight. An avalanche initiator system is also an option to avoid safety issues in mountain sports areas.

Other types of sensors can be implemented on custom modules, such as a Geiger counter or a particular matter sensor for air quality research. The structures for these sensors can be custom made by using 3D-printing technology to reduce production cost for a custom device. Secondly, a multipurpose payload module to carry a wide variety of payloads to provide necessary supplies to remote places, such as mountain huts.

11.3 Verification & Validation

The type of verification and validation (V&V) that is being referred to in this section is the system engineering definition of V&V. "Verification: Proof of compliance with design solution specifications and descriptive documents. Validation: Proof that the product accomplishes the intended purpose based on stakeholder expectations." [44] Verification can be done in four ways, namely inspection, analysis, demonstration and testing. The most adequate and cost effective solution should be chosen.

Verification Efforts

Below a selection of requirements is listed that need verification accompanied by a description how verification should be performed.

- MH-SYS-10: This requirement can be verified by demonstration. The operation costs of Nora are low so it is cost effective to demonstrate this. It does not require high skill to fly the aircraft for two hours.
- MH-SYS-09: This should be done by analysis, it is hard to recreate these operating conditions artificially and the team has no direct access to facilities that can create these operating conditions.
- MH-SYS-08: The altitude can be related to air density values in which Nora has to perform. This allows the requirement to be verified by analysis so no on location testing is required.

Validation Efforts

Validation should involve four steps, namely end-to-end information testing, mission scenario testing, operation readiness testing and stress-testing. The purpose of end-to-end information testing is to demons A number of aspects of Nora that have to be validated are elaborated upon. The mission scenario tests

[3]Infragram DIY Plant Analysis Webcam, URL `http://www.adafruit.com/products/1722`, [cited 24 June 2015]
[4]Fourth Generation Long Term Evaluation Advanced, URL `https://nl.wikipedia.org/wiki/4G`, [cited 24 June 2015]

will validate the system in flight like conditions, after which the operational readiness tests will prove that the mission can be performed with a real timeline. The stress-testing is to show the performance of the system in a variety of operating conditions. Subsystem requiring V&V are listed below

- **Controller** It is shown in computer simulations the controller is able to control the aircraft, however, the aircraft characteristics are estimates and differ from the real aircraft. Also input data is obtained from sensors which also introduce measurement errors. Therefore End-to-End information system testing has to be done to make sure the interfaces function properly and the customer can have the intended user experience.
- **Package drop** Testing must be performed to validate the content package is damaged on impact. The package contains a device to establish a communication link with the missing person, which should survive the impact under all circumstances.
- **Communication** The communication system makes the essential link between the SAR notification when *Nora* detects something and cannot give input commands. The primary concern should go to the system switch between line of sight communication and satellite communication. The communication subsystem is made up of off-the-shelf components. These components should undergo a mission scenario test to ensure the communication range in sufficient in practice compared to the specifications. If the individual components are found satisfactory the switching between line of sight communications and satellite communications should be subjected to a operational readiness test and stress tests to ensure it functions as expected.
- **Structures** Structural stress calculations should be validated by testing in a test rig.
- **Aerodynamics** The primary means of validating the aerodynamics is by doing a wind-tunnel test.These tests can be used to validate the values as provided using XFLR5.

A detailed verification and validation plan for the thermal camera sensing system, which is the primary payload for the mission is schematically illustrated in Figure 11.4. The first step is to demonstrate the compatibility of the components that make up the system. The detection software is tested on the images from the thermal sensors with the zoom lens, to check whether the image quality is suitable for detection. Secondly, a vibration test should be performed to simulate in flight disturbances to test the robustness and structural integrity of the sensing system. The imaging software is also put to test to reproduce an image suitable for production.

The mission scenario test involves flying over different terrain types at a number of heights with a test person that should be detected. From the performance results, the model for the detection software can be improved. More reliable information on the critical dimension for detection can be obtained to input in the model. The operations can then be adapted to obtain the desired performance of the detection system. The Jasper National park Canada Safety specialist is interested in the project and prepared to help testing.

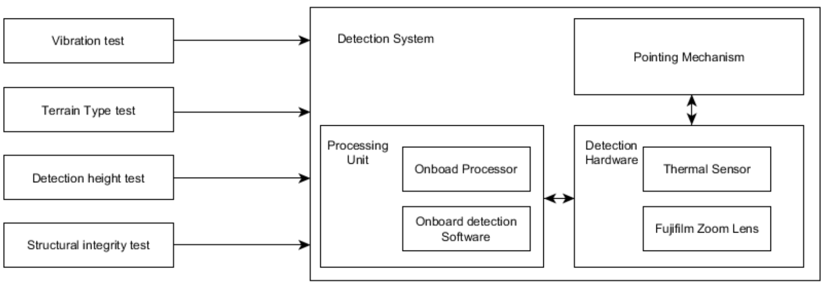


Figure 11.4: Verification & Validation of Detection System

12 | Conclusions

As part of the Design Syntheses Exercise (DSE) at the Delft University of Technology, an Unmanned Aerial Vehicle (UAV) is designed to assist search and rescue teams in the mountains. The device is called *Nora*. *Nora* should be portable by men on foot, be able to locate missing people and deliver a $2kg$ first aid package. This report focuses on the preliminary design of the search and rescue assistance UAV.

Nora will accomplish her task by employing a hybrid (UAV) design. This allows for vertical take-off and landing combined with efficient cruise flight. This results in an endurance of 2 hours with high potential to be increased by adding more fuel. *Nora* is always capable of communicating with the operator because she is equipped with line of sight communication as well as satellite communication to extend her operating range. The communication between the operator and *Nora* can be done using a tablet which is able to run the custom *Nora* communication application. In this application the operator can determine in what mode *Nora* has to operate and give essential information about the missing person to the UAV. In order to detect missing persons *Nora* has a range of detection sensors. The main sensor is a thermal camera with variable zoom lens that can be controlled along two axes for stabilization. The system can autonomously detect with a probability of detection of 90%. An area coverage of up to $34.6km^2$ per hour can be achieved. As an example: one ground searcher can cover an area of about $0.5km^2$ per hour. This means the system is the equivalent of 30 ground searchers.

The underlying technical design can be divided among the following engineering disciplines: aerodynamics, power & propulsion, structures & materials and control. The aerodynamic design features a main wing and vertical tail in the back and a canard in front. The power and propulsion relies on a combustion engine to generate electrical power. The electrical power is used to power 4 hover engines, 1 cruise flight engine and other subsystems. The cruise propeller is a push-prop located at the rear end of the fuselage. Peak power can be provided by a battery during hover and cruise mode. The structural design is able to withstand a load factor $12g$. In order to make the drone carryable by rescue operators, the structure is separable. The tail, canards and wings can be separated and the package can be taken out and divided over three backpacks. The connection mechanism is easy to use allowing for rapid deployment and stowing of the device. *Nora* is an unmanned aerial vehicle so it will control itself and react on inputs from the operator. This is done using an advanced custom control system which is able to stabilise and maneuver *Nora* to target locations. The control system controls the four hover engines, the cruise engine, the combustion engine and the control surfaces. The control surfaces (elevators, ailerons and rudder) are controlled by five servos.

Nora will have to fly mainly in mountainous regions in which it will have to encounter several different weather conditions. *Nora* will therefore be able to operate in temperatures ranging from $-40°$ to $+60°$ Celsius. As *Nora* will also encounter windy conditions, her structure was designed to withstand gusts up to $100km/h$ and a winds up to $80km/h$, making her able to deploy in almost every condition.

Once the missing person is found, he/she might need some help. Therefore a custom first aid kit will be dropped close to the location of the missing person. The first aid kit contains some products which can help the mission person such as: a mobile phone, water, calorie bars, water purification tablets and so on.. The first aid kit can be dropped in 2 ways depending on the weather conditions and the environment where the person is situated. If possible, *Nora* will land and deliver the first aid kit to the missing person. If this is not possible, due to trees for example, the first aid kit will be dropped from a higher altitude at a safe distance from the missing person. The first aid kit is enclosed in an impact shell and an attenuator, which is designed to protect the content of the package on impact with the ground.

A return on investment analysis showed a break-even point would be reached at a minimum cost price of €$25,000$ for an optimal debt-equity ratio of 15% assuming 123 *Nora*'s would be sold according to the conducted market analysis. This would entail a compounding yearly net cash profit of 5.2% or 42% for a five year period.

Nora will be a hybrid UAS that weighs $15kg$ including fuel and payloads of which the UAV weighs $11kg$. This system can easily be carried be three men on foot. *Nora* is capable of detecting missing persons in an area of $34.6km^2/hour$. *Nora* shall cost €$25,000$.

13 | Recommendations

To further improve the design in subsequent design phases, recommendations are given for future improvements.

For communications, it is advised to do further research on systems that are commercially available with larger data rates than our current capabilities. It is known to be possible, but the found solution by DJI is the only one with such a high data rate and range is really expensive. Lowering cost and increasing the data rate in communication is therefore a large opportunity. An increase in data rate adds a lot of extra possibilities to the system. Such as a video live stream with a doctor.

For the detection hardware, the sensors are connected to the detection processor via USB, but a direct connection to the FPGA would decrease the latency a lot. Therefore to achieve real-time processing of the images, an interface board is a major suggestion. Software related improvements can also be made. The program should be written using the Open Computer Vision (OpenCV) library, which is free to use and aimed at real-time vision computing. It can also be used across different platforms.

On the topic of structures and materials it can be recommended to also design the fuselage to be separable into two parts. This requires an overhaul of the internal layout as well as a redesign of the power and propulsion subsystem. However, it does greatly improve the backpack transport from a pragmatic perspective, because it greatly reduces the height of the backpack in which the fuselage is carried. Another structural consideration to further reduce the structural mass by employing topological flow optimisation on the Airex foam. The Airex foam is a major contributor the structural mass.

For aerodynamics, large drag reductions could be achieved by redesigning the shape of the landing gear, which are currently designed from a practical point of view without any aerodynamics. Studies have shown a 24% drag can be achieved [33]. Additionally a lot of research has to be done into the coupling effects of rotors and wings placed on the same device. There are currently no available tools to do such an analysis, however wind tunnel tests can be conducted using a prototype of the device.

In the future some improvements to the controller have still to be made. First and foremost the point following method of the cruise controller should be upgraded to a path following method. The main reason for this is that in a path following method the integral controller allows for compensation against wind. This compensation is not present in the current point following method. This means that even though the desired point is always reached, it is not reached along the desired path. Once the aerodynamic characteristics are more extensively analysed, the PID gains can be tuned. This can be done manually, but using a Gradient-Descent Based Extremum Seeking Method may prove to be more efficient [52]. Finally many small adaptations have to be made to anticipate all foreseeable situations. These include but are definitely not limited to evasions from objects, landing, take-off and pointing towards a target.

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