Master thesis

Design of a compact and mobile 3D Printer

to be part of a larger swarm robotics system inspired by termite builders.

Lorenzo Worang | 4393465
MSc Integrated Product Design
Chair: Jordan Boyle
Mentor: Jun Wu

Summary

This project was focused on designing and prototyping a mobile robotic builder using additive manufacturing. This robotic builder is meant to be a part of a larger fleet of robotic builders that use swarm based strategies to build structures using simple behavioral rules. The concept was inspired by the biological phenomenon that are termites, whom are able to build large mounds with complex structures and architecture on the inside without having a centralized control unit. Separate agents that are able to efficient and effectively collaborate.

The project focused on designing a singular robotic builder for that context. The builder is supposed to be mobile, compact and able to climb its own structures. The builder was also supposed to utilize fused deposition modeling (FDM) printing as its main method of building, mimicking the depositioning of dirt by a termite.

Various brainstorm theories and processes were used to conceptualize different form factors of the robotic builder. All of the concepts were evaluated using standarized methods and further developed.

The final proposed design consists of two main components, the mobile platform and the 3D printer. The design incorporates a SCARA robotic arm for the 3D printing as it has many good properties that fit the context of the project while remaining relative simple in terms of kinematics. The mobile platform includes a whegs system to be able to climb its own printed structures and a leveling mechanism to be able to print in various orientations. The mobile platform was not further developed.

Iterations of the SCARA design were done using CAD software to reduce the development time. After evaluation, a final design was chosen that combined all of the best traits of the previous designs. The design's main traits were that it was lightweight, simple, bare bones and highly customizable. Relative easy assembly was important as the design will be open-source. Off the shelf components were evaluated on its capabilities and integrated into the system as fit.

The final prototype, a SCARA printer, was able to produce promising results. The prototype was able to print faster than regular printers, print stronger structures and still be sufficiently accurate.

Additionally, a voxel based printing strategy was proposed to help improve the print time more and reduce material usage. The voxel-based approach offers the advantage of enabling a system to be fully optimized for its specific voxel requirements. It also simplified the process and strategy of using FDM-printing in a less controlled environment.

The project provides a foundational design for future SCARA printers, paving the way for continued advancements in swarm robotic construction technology. The final SCARA design is highly customizable and adjustable with firmware that matches those traits.

Although the project lays down a well thought out foundation, a lot more research and work must be done to properly develop a robotic builder that is ready to implement swarm strategies. The most crucial aspects are mobility, leveling and consistency. Additionally, further optimization of the SCARA printer as a whole and its voxel strategy is necessary.

Acknowledgement

I want to thank all of my friends and family members that have supported me throughout this project. They were the ones who reminded me to enjoy the ride and be proud of the results.

To my chair and mentor Jordan Boyle and Jun Wu who helped tremendously during the project and believed in it even through a very rocky start. And for helping me making the hard choice to limit the scope of the project to produce better results.

And to the people at the IDE faculty who pulled me out of my tunnel vision from time to time.

Table of content

Figure 1: Artwork of a termite mound and its complex architecture Retrieved from https://www.dkfindout.com/us/animals-and-nature/insects/insect-colonies/

1 Introduction

In the field of design engineering, many people draw inspiration from nature. We are not the only species that is capable of building and crafting. Many organisms, such as birds, beavers, and termites, are capable of building complex structures. Termites, especially those of the subfamily Macrotermitinae found in Africa, the Middle East, and Asia, are particularly impressive. They can build tall and complex structures that contain various chambers with different purposes (see fig. 1). These termites use only their own saliva and dirt from their surroundings to build. The "royal pair" of termites, who are capable of reproduction, have an array of loyal workers and soldiers that work together to build grand structures. The most remarkable aspect of the termite workforce is the fact that these numerous builders are able to work together without any centralised control unit. All of the builders use basic behavioural and interaction rules to work together, even as independent agents. This decentralised process or swarm strategy can be applied in many applications. Decentralised manufacturing processes using additive technology can be particularly interesting for several industries. In this project we try to lay out the base for a robot builder that uses the same swarm strategies. We do this by designing the hardware that could be applied to such a system.

Context

The construction industry remains one of the most dangerous sectors in the world, with a high relative fatality rate according to the Occupational Safety and Health Administration (n.d.). Given that the industry is estimated to grow to a worth of $15.5 trillion by 2030 by the Global Construction Perspectives and Oxford Economics (2017) , there is a strong demand for novel and safer procedures in this industry. This need is further highlighted by the deaths of thousands during the preparation for the World Cup in Qatar (The Guardian, 2021) To address this issue, the modern world is looking into automating tasks that are too tedious, complex, or dangerous with technology.

A decentralised automated manufacturing process can also be beneficial in regards to troublesome environments. Disaster, extraterrestrial or even environmental protected areas can be difficult to work in using regular manufacturing processes. "Robots could be the only viable alternative for construction and manipulation tasks in environments that are hazardous or inaccessible for humans" according to Soleymani(2015). This automation also reduces the human footprint left in construction zones. Projects such as the TU Delft's own 'Zebro' robots explores the possibilities of swam systems in extraterrestrial areas (3Dnatives, 2021).

Autonomous builders are not new, and many researchers have explored designing and creating such systems in various forms. The Harvard TERMES project for instance focuses on swarm robotics by using prefabricated building blocks, where the TERMES robots can work

together using simple rules and traverse their own structures to build further (Petersen, 2011).

FDM manufacturing has also been scaled and implemented in real-world applications, such as concrete printers that can fully 'print' houses in various geometries. These printers come in various sizes and versions, and work is underway to make them more mobile (Tiryaki, 2019).

At IDE TU Delft, students have worked with Voxel Construction Systems, which use cellular structures that are easily attachable and detachable. The idea behind these simplified building blocks is that they can be easily assembled by robots. Biront (2022) focused his thesis on simplifying the assembly process even further.

Assignment

The task is to design a robotic builder that can use amorphous materials to construct structures and use its own structures to expand its build space. It can do this by being mobile and by climbing its own structures, effectively expanding its build space in all directions. Amorphous materials were chosen because the system could adapt to the different geometries of various environments. In this scenario we will be specifically looking into Additive Manufacturing (AM). This type of manufacturing can also help in creating more efficient systems, only build what you need. For example, adding small structures to collapsing tunnels as suggested by the Zebro team (3Dnatives, 2021). However, an autonomous and decentralised system may have practical limitations. The challenge is to create a system that can build on its own while still being viable in terms of speed, reliability, and capacity.

This project seeks to validate the performance of a single robot builder that has the potential to be part of a larger team in the future. This larger swarm team may be the solution to 3D printing's main barriers into mainstream manufacturing which is the print size and print speed (Poudel, 2020). The swarm strategy can be quite simple, like implementing a state system as proposed by Carey (2021). Wherein the robots go from state to state, for example "looking for build material" state into a "building" state. But for this project, designing the swarm strategy will be out of scope. An integrated system is essential to validate the concept, so mainly off-the-shelf components must be used. Research has shown that similar systems can operate up to a certain degree. The capacity, accuracy, and mobility are limiting factors that should be covered. This project will implement a system-level integrated approach, meaning that the novelty comes from integrating different aspects / solutions into one system.

The solution to this project can help lay the groundwork to integrate swarm robotics in the construction industry effectively, providing a solution that can improve the industry as a whole.

Research objective

With this project we hope to deliver a proof of concept for a team of robotic builders based on swarm tactics. Another research is done parellel to this one by a peer, that research will focus on the swarm strategy and tactics.

This assignment requires the student to design and experimentally evaluate a mobile additive manufacturing robot capable of building three-dimensional structures. The robot should be able to climb the structure as it is being built. The focus will be on hardware integration at the systems level.

2 Research

Additive Manufacturing

3D printing or Additive Manufacturing(AM) is the process of creating 3D structures out of a digital model. AM has become more popular in recent years due to developments in desktop 3D printers, making them more budget-friendly and therefore more accessible. There are many types of 3D printers that all have their respective up- and downsides. The most well known types of 3D printers are:

1. Fused Deposition Modeling(FDM)
2. Stereolithography(SLA)
3. Digital Light Processing(DLP)
4. Continuous Liquid Interface Production(CLIP)
5. Material Jetting
6. Binder Jetting
7. Selective Laser Sintering(SLS)
8. Multi-Jet Fusion(MJF)

For this project the focus will be on FDM printing, which consists of extruding plastic filament on a surface layer-by-layer. FDM printers can be found in many homes and therefore also experienced a lot of development. These printers are getting faster, more accurate and more compact. This type of printer has a large range of filaments that it can use, even many more sustainable solutions such as reused eggshells(Donders, 2022). All of the factors suggests that FDM is a good choice for the robotic builder especially because of its vast and supporting community, in addition to the versatility of the system.

FDM Printer Components

To be able to implement FDM technology into the robotic builder, it is important to know what is essential for a 3D printer. More importantly, are there components that can be omitted to simplify the system? To get a better understanding of the system a component tree is created, see figure 2 to the right.

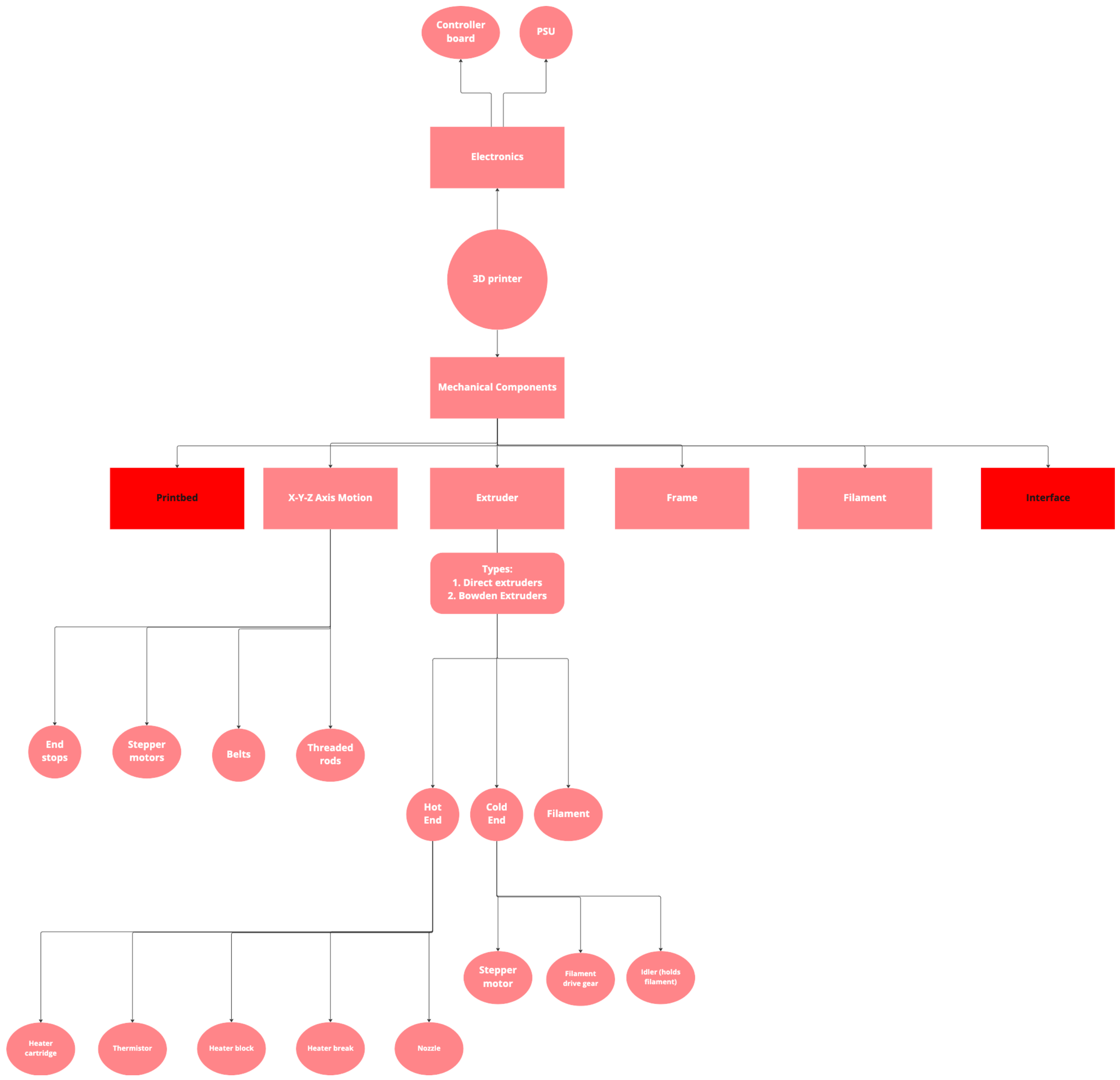


Figure 2: Component tree of a FDM printer.

Mechanical components

The extruder unmistakably extrudes the filament onto the build surface to create the prints. The extruder consists of a 'Hot End' and a 'Cold End'. In general the cold end holds all the parts and pieces that guides the filament spool into the hot-end. The cold end is also often referred to as the cooling zone found on the printhead. In the hot end the filament goes through sections that melts the material and extrudes it onto the surface via the nozzle (see figure 3). There are two main extruder types: Direct drive and Bowden extruders.

Direct Drive Extruders

Direct drive extruders (figure 4) will have its cold end directly attached to its hot end on the printhead. The filament will travel an insignificant distance before reaching its hot end. In general, direct drive extruders are implemented on machines that print with more unique materials that for instance only work with higher temperatures. The direct connection avoids issues such as clogging.

- Minimises chance of failures between hot and cold end
- More precise and responsive extrusion
- Requires less motor torque
- Generates more heat on motors
- In general slower print (due to weight)
- Can print most types of filament

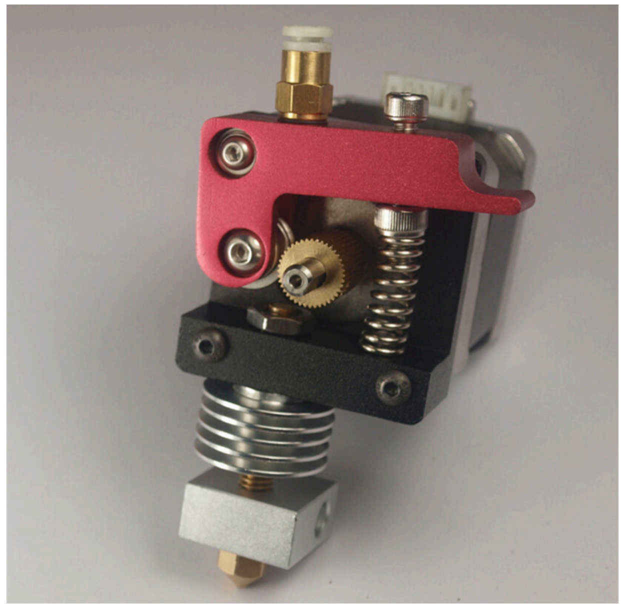


Figure 4: Direct drive extruder. Retrieved from Steemit, by Boucaron 2017, https://steemit.com/printing3d/@boucaron/3d-printers-remote-direct-drive-extruders-overview

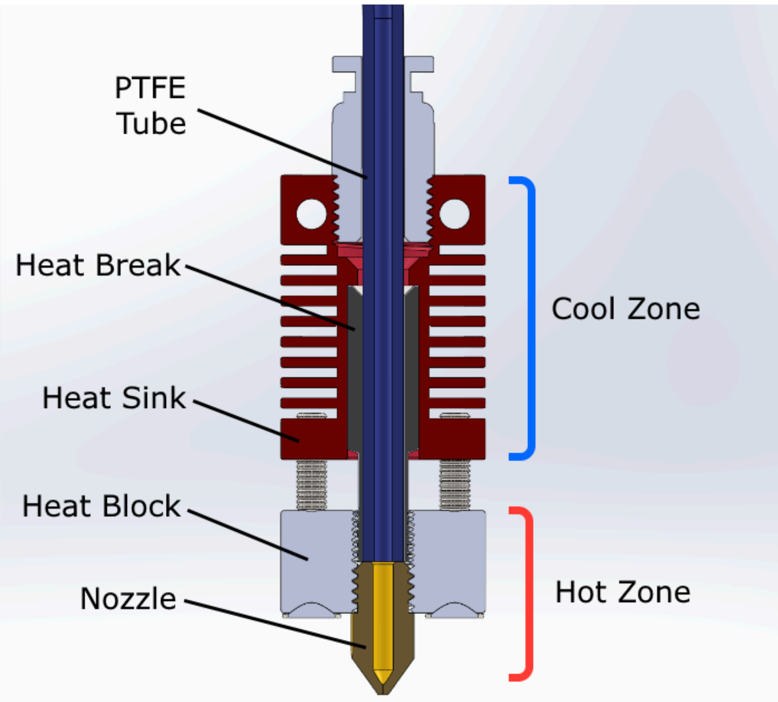


Figure 3: Cross section of a hot-end where a cooling zone can be found. Adapted from Creality Experts, by C. Garcia 2021, https://www.crealityexperts.com/creality-hot-end-repair-guide

Bowden Extruders

Bowden extruders can be found in most commercial low-budget FDM printers. The 'Bowden tube' is a PTFE tube that connects the cold end (which is positioned somewhere else than the printhead) to the hot end. That distance does mean that there is slightly more chance of failures, what you get in return is a lighter printhead.

- PTFE tube connects cold end to hot end
- Lightweight printhead
- Able to print clean on faster settings
- Worst extrusion control
- Adjustments needed for specific materials

Print bed

The print bed or build surface of a 3D printer usually serves two functions. First, the bed itself is connected to one of the stepper motors and moves in the y or x direction. Secondly, the print bed also heats up. Heated print beds primarily prevent warping. Warping is a phenomenon that causes the bottom layers of a 3D print to "curl" up due to contractions caused by the material cooling down (Alsoufi, 2017). The heated print bed improves adhesion to the build surface and therefore prevents warping. However, heated print beds are not essential for 3D printing. Warping mostly causes precision and aesthetic errors, but nothing structural. In this build, the robot must directly print on the surface, so the print bed will be omitted.

Filament

By omitting the print bed, the chance of getting warped prints increases, as mentioned above. This comes with a greater risk of adhesion failure. However, by choosing the correct filament, the risk of adhesion failure can be reduced. The most common filaments are found in table 1 here below (All3DP, n.d.).

Upon inspecting the table more closely, it seems that ABS can be promptly removed from the list of potential candidates. It requires a chamber and heated bed. The other filaments can all in theory perform without a heated bed, but with PETG it is recommended to use one. Which means its also not the best candidate for the design.

PLA, ABS, and PETG are the most common materials that can print on most machines without any (or minor) alterations. In this case, PLA is the best choice because of its lower temperature requirements, which means it has less chance of warping and is the easiest material to print with. However, PLA is relatively more brittle compared to other materials. It may be a good idea to opt for PLA+ if brittleness becomes an issue

Important to note is that there are a plethora of filaments. Foaming filaments were another option, which are filaments that foam up when heated up (All3DP, 2021). The theory was that it could add volume after being printed similar to an actual foam, but in practice it only makes prints lighter with no difference in volume. It prints significantly slower compared to regular filaments.

There are also the group of ‘ stronger’ filaments that are off the shelf and often used, nylon and polycarbonate are examples of this group. This group of filaments share the characteristic of operating at higher temperatures which means that they also need more or complicated components. Therefore these materials have been omitted from the table. A lot of more research can be done towards potential filament types, but due to time constraints it was left out of scope.

Filament type	Temperature (in ºC)	Heated bed	Chamber	Adhesion
PLA	180-210	Optional, 40-60 ºC	No	Not needed
ABS	230-250	Required, 90-110 ºC	Recommended	Tape
PETG	220-245	Recommended, 70-90 ºC	No	Tape
TPU/TPE(Flexible)	220-260	Optional, 40-60 ºC	No	Not needed

Table 1: Most common 3D printing filament types and their traits.

Electrical components

The PSU is the power supply, and the motherboard houses the microcontroller and stepper drivers that can actuate the steppers. The power supply is going to be a low voltage DC unit, and a 12 or 24 volt unit is more than sufficient. The most important part is to ensure that the power it delivers is enough to run all of the components. The motherboard is a more complex component that also partly dictates what firmware is going to be used to run the G-code(explained further ahead) and communicate with all the different components. The three most common motherboards according to Florian (n.d.) are listed below:

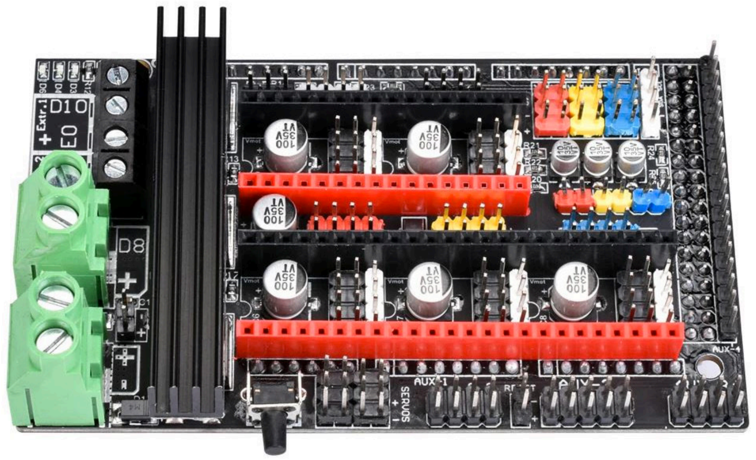


Figure 5: The RAMPS motherboard, the most used motherboard for DIY printers due to its relative cheap price.

1. RAMPS Motherboard (see figure 5)
This motherboard is actually an Arduino Mega shield. It attaches to the Arduino Mega board, making it possible for the board to drive components that use more than 5 volts. RAMPS uses an A4988 stepper driver and an 8-bit CPU. Arduino-based motherboards all use the Marlin firmware.

2. Smoothieboard (see figure 6)
This 32-bit motherboard has everything that is needed for a 3D printer in one board. The board uses its own custom firmware called “Smoothieware”. This firmware is praised for its capabilities that match Marlin but are easier to configure.

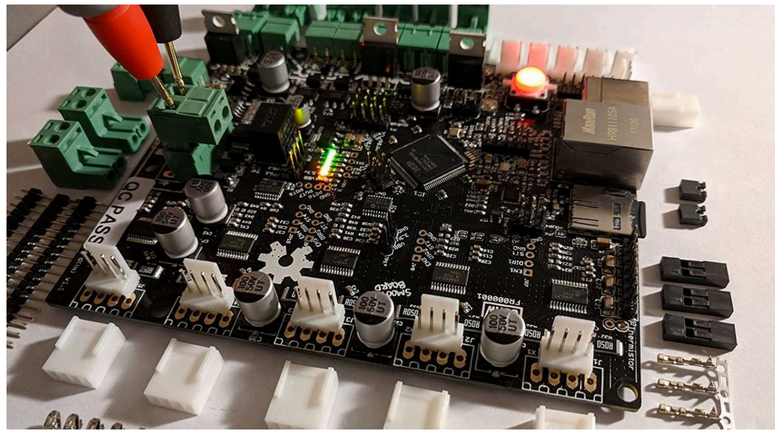


Figure 6: The Smoothieboard that uses a more user-friendly firmware “Smoothieware”.

3. DUET Motherboards (see figure 7)
The DUET motherboards are the top-of-the-line controllers in the world of 3D printing. The DUET boards have everything that you could wish for integrated into one board. The DUET motherboards also use their own unique firmware, “RepRap-Firmware”. What is unique about the RepRap-Firmware is the variety of movement systems it can control. Depending on which mechanism is used, the DUET boards may be the sole choice.

Noewadays there are a lot more different types of motherboards on the market than a couple of years ago. Most motherboards have similar components and are able to run all kinds of firmware given that the correct adjustments are made in that firmware. The biggest differences can be found in what kind of hardware they are able to support. The DUET boards for instant are able to run double extruder setups. 32-bit boards are a lot more common now too, even on the cheaper boards.

Figure 7: The high end DUET Motherboards that uses its proprietary firmware dubbed “RepRap Firmware” which includes a variety of movement systems.

G-code

G-Code is a language developed specifically for computer numerical control (CNC) machines, which are used in fabrication machines like milling machines, cutters, and routers. The commands for G-Code are input as simple text that the machines can read. G-code has various pre-defined commands that affect the movement and operation of the CNC machines, including those used in 3D printers. The G-code language is set up quite simple. Each letter and sequential number represents a specific command or operation. Following the command, specific parameters for that operation can be filled in. For example, the G0/G1 command means linear movement from point A to point B, with the parameters being a set of destination coordinates that specify where the printer should finish. So for example: "G1 X50 Y30 Z30" moves the nozzle to coordinate (50,30) and to a height of z is 30 steps. There are hundreds of G-code commands available, many of which extend far beyond simple move and point commands. G-code also has specific operational commands for various CNC machines, such as tool selection commands for milling machines, and heated bed and extruder commands for 3D printers (https://marlinfw.org/meta/gcode/). An example of some of the commands and its meaning can be see in the figure 8 here below. It is important to understand G-code, as this will be the primary method of communicating with a 3D printer.

Slicing

Slicer software is the bridge between 3D CAD models and G-code. As the name may imply, the slicer 'slices' your 3D model in layers and determines per layer the best way to execute that print. It then translates that path into G-code which the printer can read as commands for it to execute. After slicing thin horizontal layers, the software produces a series of G-code commands that instruct the printer on how to execute that one layer. This goes much further than only the path of the nozzle. The software also controls various factors such as printing speeds, nozzle temperatures, infill density, layer height, support structures and more. It will try to optimise these settings based on the 3D printer, model, filament and the user set parameters.

In general, the slicer will instruct the 3D printer to start with the outlines of the layer creating a barrier of sorts. After the initial outer line work it will start filling up the geometry with various kinds of infill patterns with different possible densities(see figure 9). The output of a slicer is nothing more than a very long text file with various lines of G-code commands that can be read by your 3D printer. The way the G-Code always starts with the outline of a print and then fills it up is important to know. When creating a mobile 3D printer the way it moves can be bounded to what the G-code instructs.

A more complete list of G- and M-Codes

For those interested, here is a more complete list of common codes.

G00 Rapid move G0 X# Y# Z# up to eight axes or G0 Z# X#
G01 Feed Rate move G1 X# Y# Z# up to eight axes or G1 Z# X#
G02 Clockwise move
G03 Counter Clockwise move
G04 Dwell time G04 L#
G08 Spline Smoothing On
G09 Exact stop check, Spline Smoothing Off
G10 A linear feed rate controlled move with a decelerated stop
G11 Controlled Decel stop
G17 XY PLANE
G18 XZ PLANE
G19 YZ PLANE
G28 Return to clearance plane
G33 Threading (Lathe)*
***NOTE**: G33 and G33.1 will not work on Sherline CNC mills or lathes because the spindle and the axis are not synchronized.
G35 Bypass error checking on next line
G40 Tool compensation off
G41 Tool compensation to the left
G42 Tool compensation to the right
G43 Tool length compensation – negative direction
G44 Tool length compensation – positive direction
G49 Tool length compensation canceled

Figure 8 : A snippet of G-code commands and their functions retrieved from Sherline. (n.d.). G-code [Screenshot of webpage]. Retrieved from https://www.sherline.com/g-code/

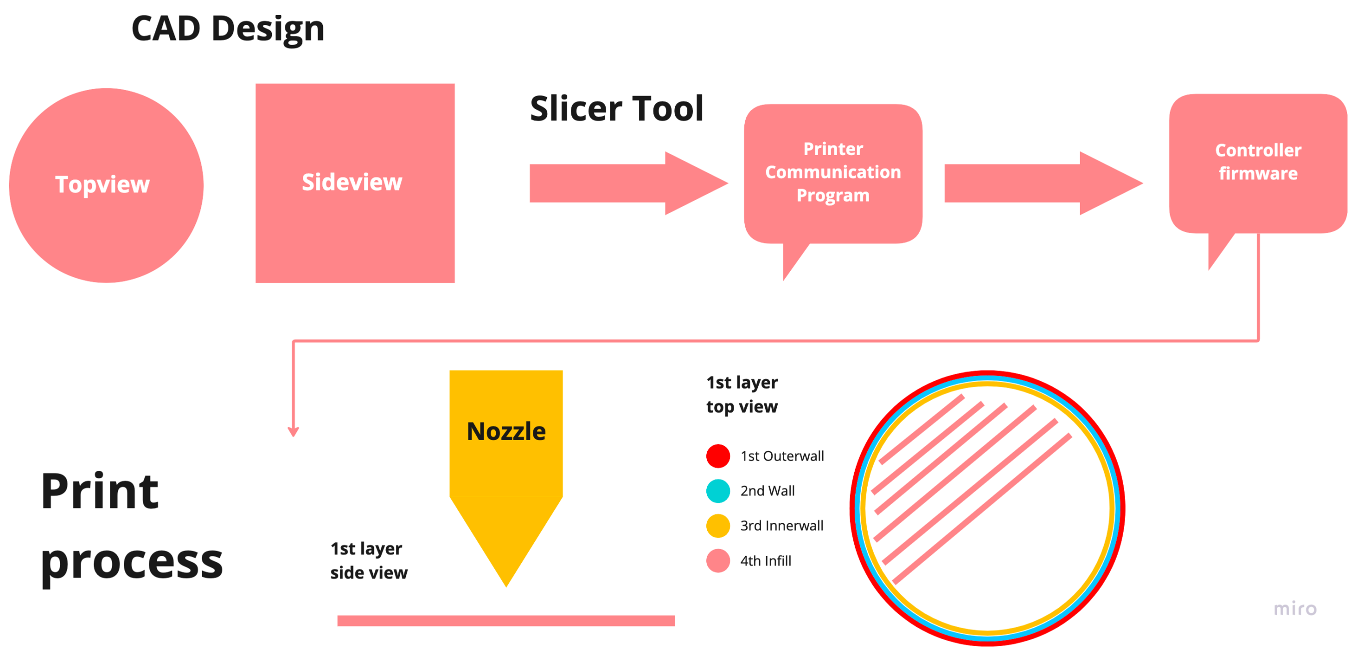


Figure 9: Flow diagram from CAD model to the very first layer set out by the printer.

Technology exploration

Swarm robotics are a relatively under-explored technology. Research has been done that apply the swarm strategies (Carey, 2021), but there are still a lot of obstacles to be hurdled before these solutions can be deployed into real world applications. While in the meanwhile AM technology is being used worldwide and keeps steadily innovating itself. This drive to improve AM technology has definitely not died down. 3D printers that are mobile, capable of printing large structures, or printing at high speeds with biodegradable filaments are all examples of how the technology is advancing in different areas. There is still a lot of untapped potential for AM technology. In this section research and technology will be explored to see what knowledge can be obtained.

Cooperative Mobile 3D Printer

Cooperative 3D printing is a novel method of 3D printing that entails several smaller and mobile 3D printers working together on one larger print. Which essentially is the same as swarm printing, but in this case they fully focus on predefined geometries. “Cooperative 3D printing is an emerging technology that aims to get rid of the “box” by putting the printhead on a mobile platform such that a swarm of mobile robots carrying different printheads can cooperate with each other on a single printing job.” (Marques, 2017). In one of the earlier papers written by AMrobots they focused on designing a mobile 3D printer to form the base of their cooperative printing system. The final concept consisted of a mobile platform, a z-stage, the main circuit and network capabilities(Figure 10). Using the WIFI capabilities of an Arduino they were able to upload the G-Code wirelessly creating a truly mobile system.

Their main way of traversing was to use 4 Mecanum wheels. These wheels gave the design manoeuvrability but also meant that their mobile printers were able to move while printing. The X and Y movement of the printhead in their design was done by moving the whole printer using its Mecanum wheels. Good to note is that the paper stated that slippage between the floor and the wheels caused inaccuracies in their printing that got worse over time. Their solution to this issue was to implement a feedback control system using optical sensors to measure the actual distances covered and correct itself. In their later iterations (no public papers were found) you can see that they strayed away from the mecanum wheels and went with a SCARA-arm design(see figure 11). Their reaason to switch from mecanum/omniwheels is not documented but it could be argued that slipping may have occurred too often, the extra computing power for the feedback loop was too much or that printing while moving was too inaccurate.

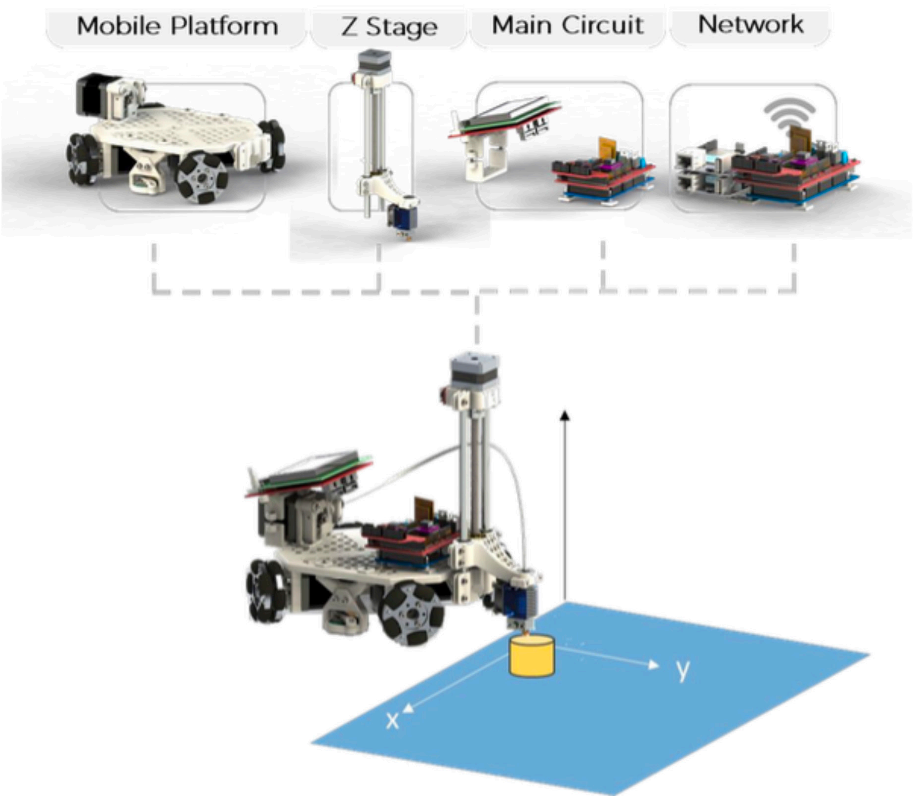


Figure 10: Concept model of a mobile 3D printer by AMbots retrieved from Marquez(2017).

Harvard Termes Project

The TERMES system is a multi-robot construction system that drew inspiration from termites and their building strategies. The system is designed to use autonomous robots to construct relative large structures. The ultimate goal is to construct human-scale structures using this innovative system.

The TERMES team had a similar vision, a fully decentralised control system that is capable of building structures in harsh conditions without requiring lengthy preparation. The TERMES robot employs custom building blocks to create structures and is capable of lifting, carrying, and manipulating these blocks(see figure 12). Furthermore, the robot can climb up, down, and maneuver on its own structures.

The team experimented with different climbing systems, a simple platform was built to implement different types of solutions such as wheels, threads and whegs. These solutions were evaluated based on their climbing height, self-alignment, and gait smoothness. The results of each solution can be found in figure 13 on the next page. The whegs performed the best in regards to climbing height and self-alignment. It performed relatively well in its gait smoothness. The final design consisted of four small whegs in conjunction with a custom building block that had additional notches to improve alignment capabilities.

For low-level control, six active infrared (IR) sensors were added to the robot and pointed towards the ground. These IR sensors gave positional feedback to the robot by reading patterns on top of the custom building blocks, which had white crosses on top of their surface. These

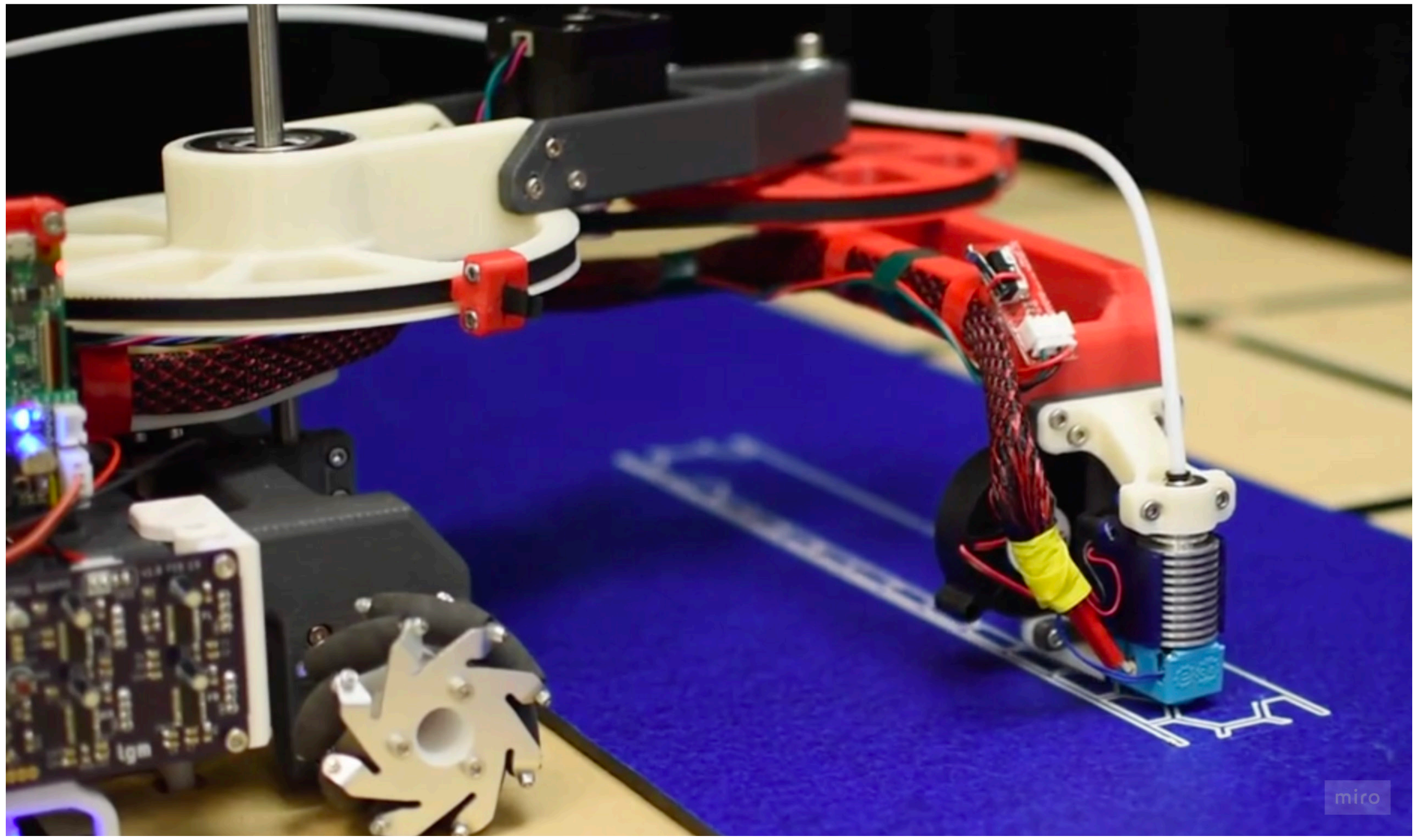


Figure 11: Iteration of the AMrobots’s mobile printer, screenshot from AMBOTS Swarm 3D Printing video (AMBOTS Inc., 2021).

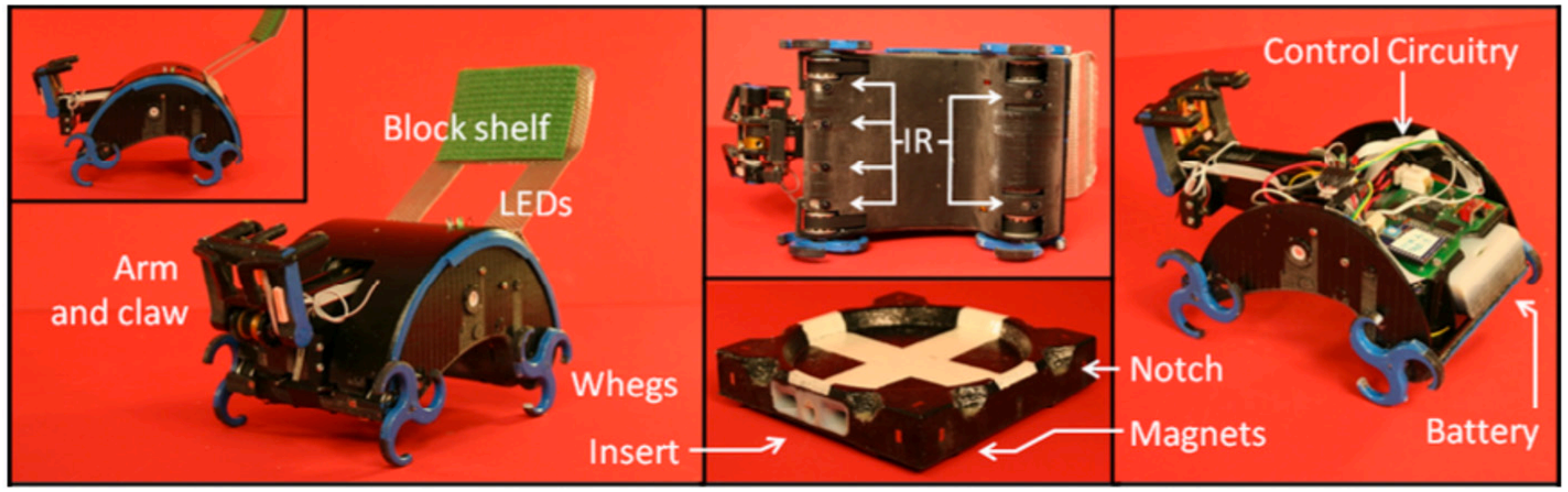


Figure 12: The TERMES robot and its arm and claw system, designed to manipulate the building blocks. Taken from Peteresen (2011).

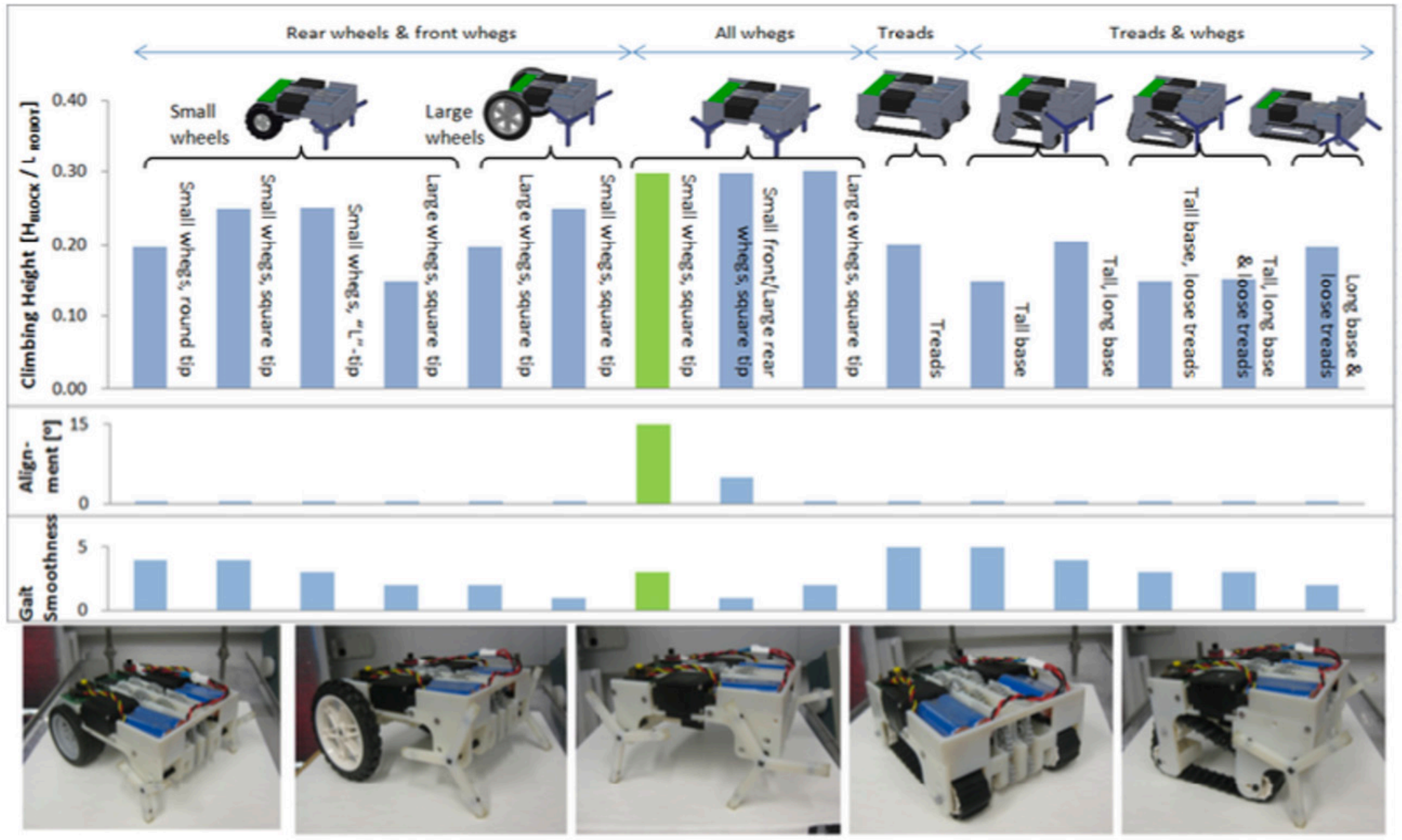


Figure 13: The results of various hardware configurations for the TERMES robot from Petersen (2011).

crosses are enough to inform the robot of its positioning using simple rules. For instance, if the IR sensor picked up on the white cross in meant it was aligned. If it senses a black surface, it meant that it was a few degrees misaligned(see the previous figure 12). The robot can also rotate freely on top of the block using a differential steering system, which comes in handy when building more complex structures.

The building blocks can be picked up at "depots" that must be refilled manually. The system uses an arm and claw system to extract the blocks, shelf them on itself, and then place them on top of another building block. The idea was to use a simple system supported by passive mechanical features that improved alignment and attachment.

The paper proposes an algorithm that can compile a predefined structure into a "structpath" representation(figure 14), which is a path that includes the stack-height at each point. This target representation, combined with the proposed algorithm, can seamlessly build large structures with multiple builder units.

Cementitious Additive Manufacturing Robot

When looking at a singular robot many strategies can employed for it to be able to build. In the case of the system that was designed by Burns (2020), the process is similar to FDM printing by thinking in layers. The robot designed by Burns was able to lay out cement to build structures and spray out foam to overcome obstacles and increase height(see figure 15). The robot would leave a trail of cement similar to a snail, also in layers. It uses a frontal object detection system that consists of various sensors.

If the objective is to reach a certain 'location A' at a certain height, the system would lay down a layer foam and then detect if it is able to reach the specified location. If the system determines it isn't able to reach its target location, it will lay out a second layer and so on until it does not detect an obstacle anymore(see figure 16). This is one of the simplest strategies to use when the object is to reach a specified location.

Furthermore, this system is able to detect chasms and fill them up so the robot can continue his path (see figure 17). This chasm detection system and the ability to 'build' downwards adds a lot construction options to the system. In this case the system uses a PU foam though as mentioned here above, which 'shoots out' at reasonable distances. When using FDM printing the nozzle has to touch the surface it wants to print on. This requirement makes it more difficult and time consuming for the robot to overcome obstacles or print in awkward orientations compared to the Burns system.

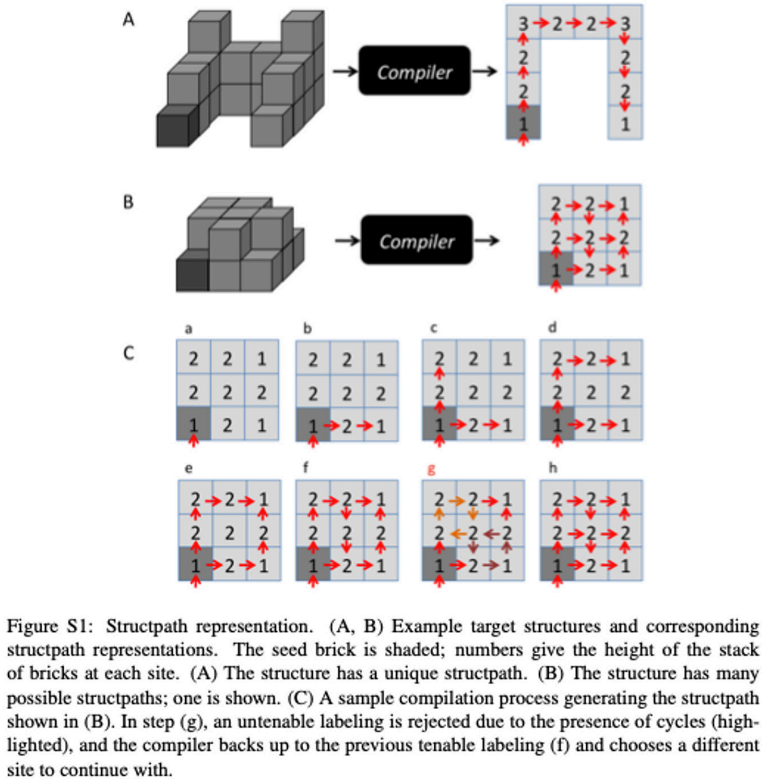


Figure 14: The proposed 'structpath' representation by Peterson(2011).

Main takeaways

Bowden Extruder

To align with our objectives for the mobile builder, it would be wise to design a 3D printer using the Bowden extruder setup. Wherein direct drive extruders improve print quality and reduces the

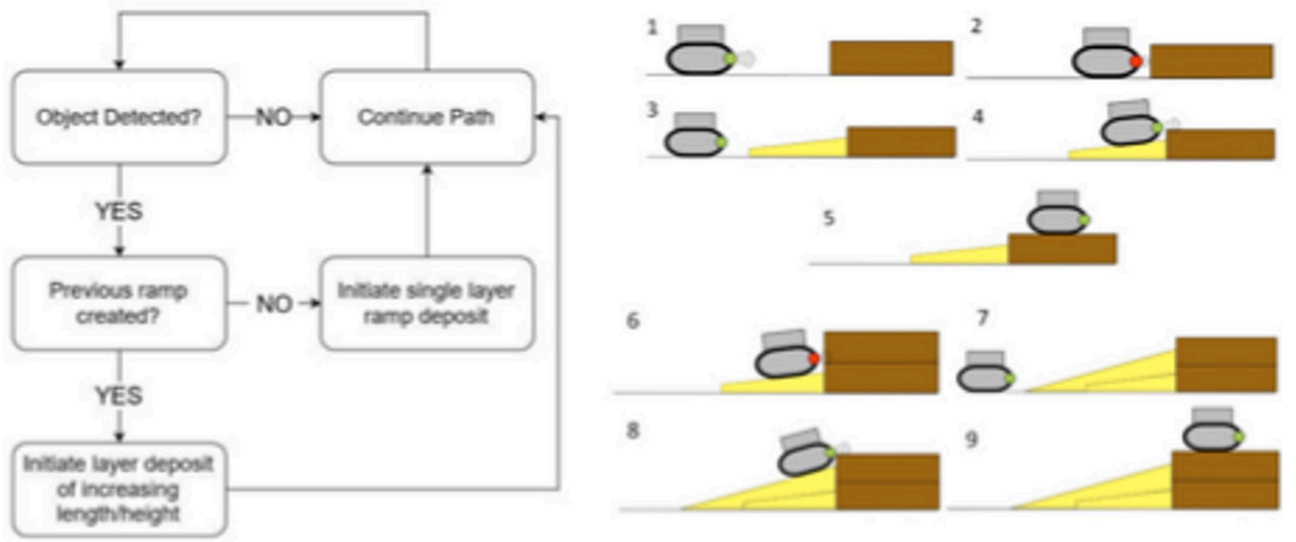


Figure 15: A flowchart illustration of the obstacle detection system and building process of the robot builder system designed by Burns (2020).

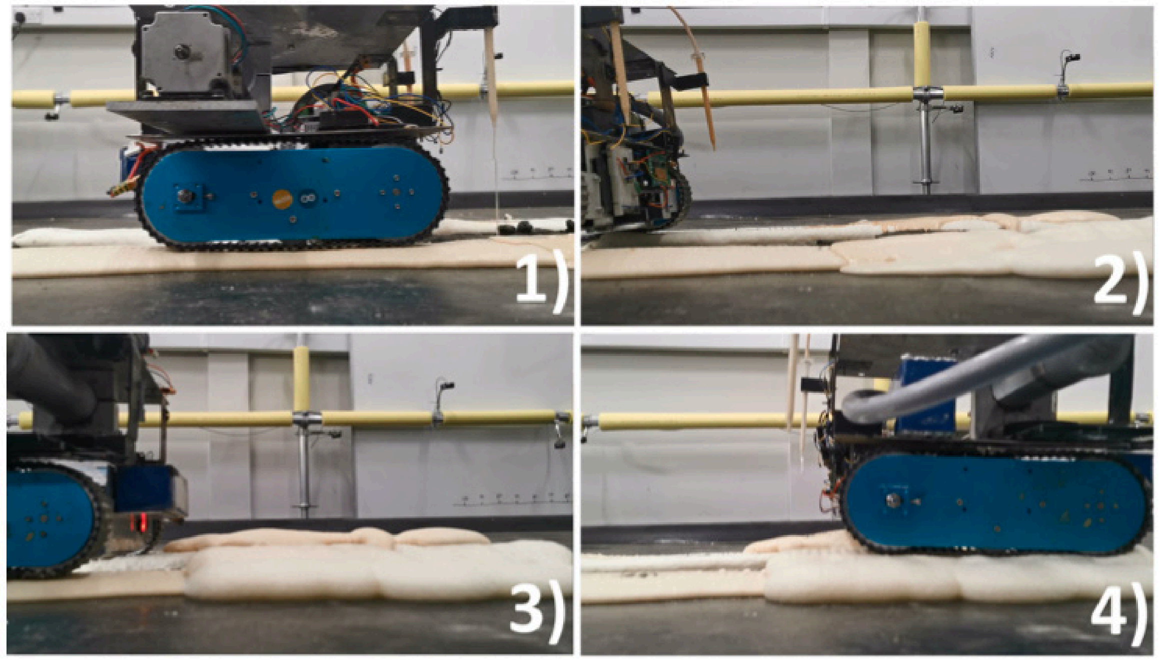


Figure 16: Snapshots of the Burns robot (Burns, 2020) detect the first cement layer, spraying out PU foam to create height so it is able to lay down a second layer of cement over the first one.

chance of failures, the Bowden extruder can help create a more mobile and faster system. A lighter print head means faster movement and less rigidity is required for good prints. Most of the benefits of the direct drive extruders will be pointless to have in the suggested system. The motor torques that are required for our proposed footprint will be relative insignificant, we will only print with PLA and it is highly likely that FDM will be used for prototyping which could melt with the additional heat from the motors. Therefore all of the signs seems to point towards a Bowden extruder.

No heated bed

When utilizing a system that omits the heated print bed, added attention must be given to the filament choice and print settings. Otherwise, warping and adhesion issues are likely to occur. Slightly hotter nozzle temperatures, reduced part cooling and print speed are all options to reduce the risk of having these issues. With that in mind, PLA and PLA+ seem to be the best filament types to use due to its relative low melting temperature and its versatility. No additional equipment is necessary to print these filaments with a variety of settings.

Print speed

When it comes to the printing speed of a conventional 3D printer many variables play a part. A lot of it is also dependent on the firmware and component choice, but if you were to try to list some, these three would be somewhere at the top. Heating, cooling and the rigidity of the frame. Heating and cooling can be improved by upgrading components and strategically choosing filaments as previously mentioned already. While the rigidity of the frame is an important factor to think of when designing a 3D printer. As in many cases, the more simple the system the less chance of having faults. Hopefully mechanisms can be simplified to avoid creating too many stress points that could incite deflection.

Climbing locomotion

Climbing is an important aspect of the robotic builder, without that skill it is not able to build larger structures without supervision, at least structures that require a certain height. In its most rudimentary form, the climbing solution can be large wheels. If you make sure that the structures it has to climb is not too tall, so designing stair like structures, the robot should in theory be able to 'climb' said stairs if its wheels are large enough. In this case too complex systems should be avoided, the weight and size of the printing system must be able to be balanced during the climbing process and the more complex movement/mechanism the more difficult that will become.

However, there are ways to enhance the climbing capabilities of the rudimentary large wheel system without adding too much complexity. For example using a tank track system instead of solely wheels can add in its versatility, adding grippers for extra grip or even using magnets for metal surfaces. Luckily, Peterson (2011) has tested most of the variations already during the TERMES project. The results can be found in figure 13 as previously stated.

A simple way of climbing structures without too many complex mechanical components is by using whegs as proven by Peterson (2011). These whegs are interchangeable with any system that uses wheels, which gives flexibility in regards of design. Some of the more well designed solutions require additional moving parts such as the stair climbing robot that you can find in figure 18. Which is an impressive system on its own and definitely exceeds the capability of the whegs system, but would not fit in the constraints of our scope.

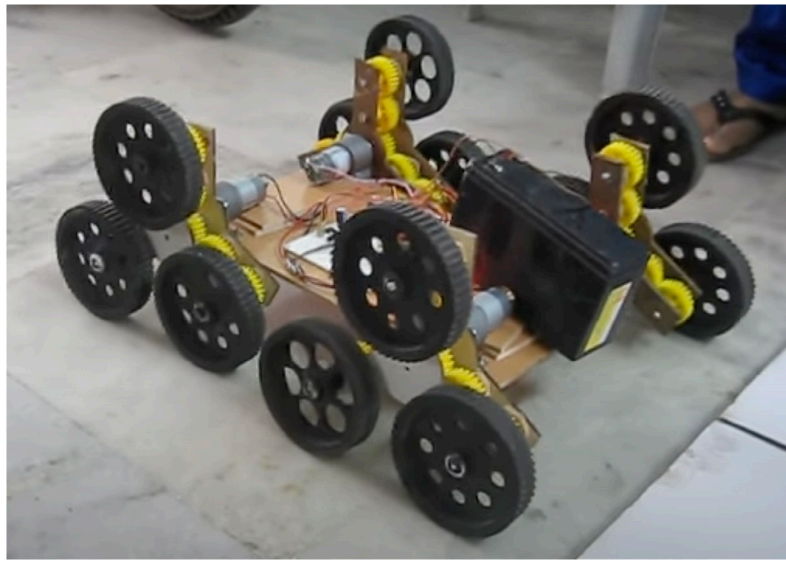


Figure 18: Screenshot of the stairclimbing robot by HVS-Engineerslab (2018) video found on Youtube.

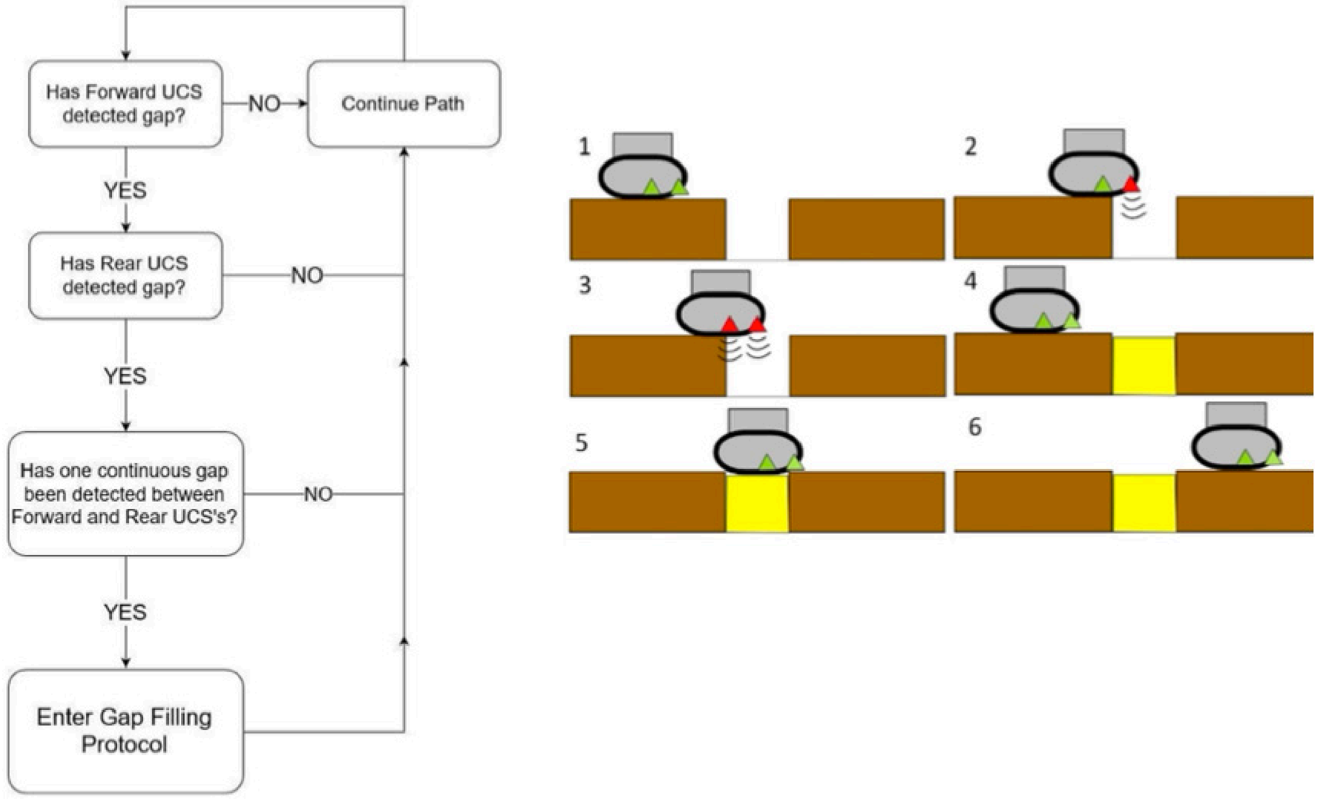


Figure 17: A flowchart illustration of the chasm detection system and building process of the robot builder system designed by Burns (2020).

3 Ideation

Building strategies

To design a mobile compact robotic builders that uses FDM technology it is important to define the possible different methods and strategies to build structures. The system requires the robot to be able to build large structures while it also needs the ability to climb these structures and print in specific orientations. The first most obvious requirement is to make sure that the robot can climb its own structures by being able to print wider structures than its own width(Figure 19).

Goal

To gain a better understanding and overview of the various types of strategies available to the robot, we need to first define a goal. Otherwise there would be too many strategies and tactics to discuss. The goal that we set for the builder is:

The robotic builder needs to reach a point A that is a certain distance away from the robot, but is also placed at a higher point than the robot. It must reach this point by building structures and utilizing these structures by climbing them.

(See figure 20)

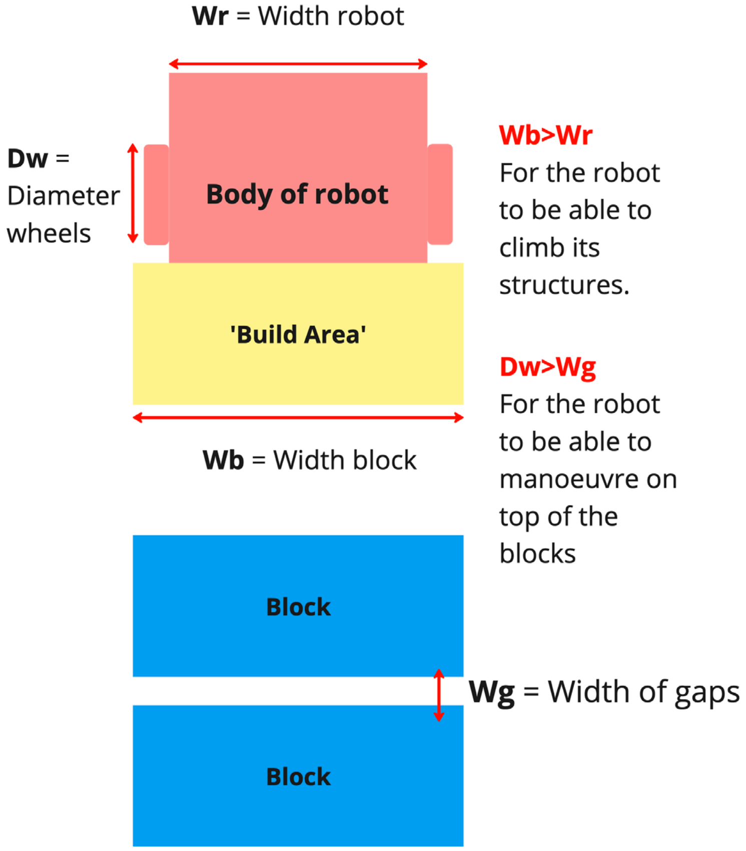


Figure 19: Topview illustration of the robot builder and its dimensions, build space and block spacing.

Essentially, there are two primary methods for the robot to reach location A. These two methods or 'strategies' are 'forward printing' and 'backward printing'. Good to note is that these two strategies are not absolutes, in more ways than one they are actually complementary to each other. But we will discuss this further ahead.

Figure 20: The robotic builder (on the left) that has the goal to reach a specific point A on top of a structure. It must reach the structure by building its own ramps.

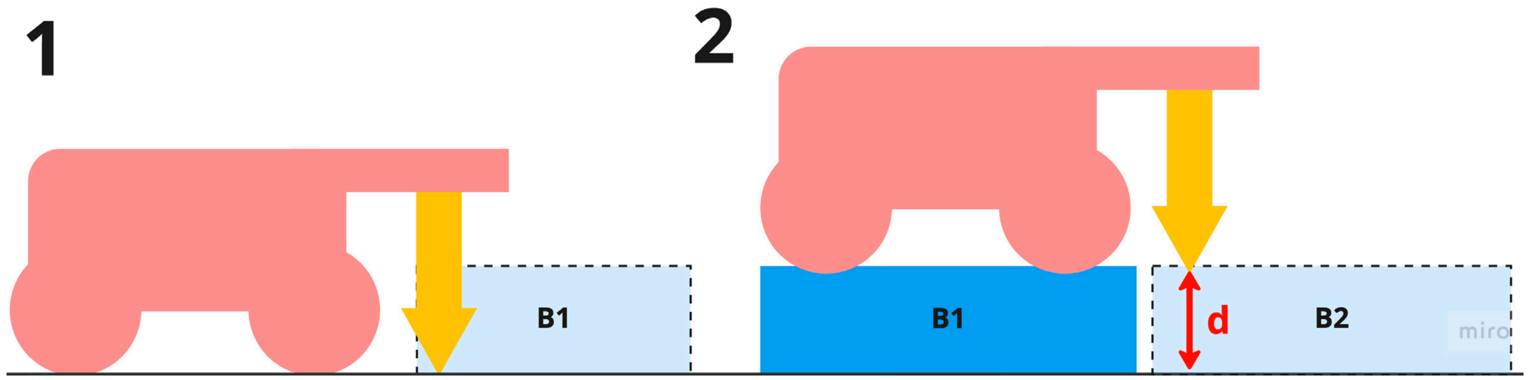


Figure 21: When printing forward, the builder needs to be able the print at different levels. At least a distance d below itself.

Printing forward

When we print forward it is similar, but not identical to the method previously described and used by the Cement Builder developed by Burns(2020). However, the Burns robot only prints forward using PU foam and not with the actual construction cement mix. This strategy means being able to build structures by printing building blocks in front of it. This means that the system requires the ability to climb structures but also to be able print blocks at a different level from it self. As can be seen in figure 21, when it prints forward, it for example needs the ability to print one level (distance d) below itself to continue at the same level. The Burns system is able to shoot out PU foam in front of it, drive over it and then shoot out foam again at the end of a layer. It does not have to adjust for the height difference created by the first layer due to its ability to shoot at a distance. In our case we need to employ some kind of mechanism that makes sure that the nozzle can enter negative z-space. Another issue that can arise with forward printing is when the builder's size exceeds the supporting area of the structure For example, during printing of the first layer, there is going to be a point at the start where it has not printed a sufficiently 'long' structure yet. Therefore the robot will be angled as shown in figure 22. In this case, the robot must be able to level itself in some way for it to continue printing a proper layer.

Printing backward

A less complicated strategy of building is the backward printing method. This method is similar to what the Harvard Termes builder does when building larger structures. (figure 23). With this approach the builder essentially leaves a 'trail' of structures like a snail leaving trail or in the case of the Termes builder building blocks. In this case the robot would leave a trail of FDM printed structures. When using this method, there is no need to be able to print at different levels, eliminating the requirement of self leveling. The main drawback with this method is efficiency and printing time. If you look at figure 25 you can see that this strategy requires the robot to always overprint in the length when it needs to build in height. When L is the required length of block B2 and b the length of the robot itself, then the first layer B1 has to be the sum of L and b. In larger structures this could result in a lot of additional printing time and filament usage. In forward printing this is also the case if several layers/levels needs to be built, but in essence it is able to print a layer while it is not fully supported, it will be able to level itself. But when multiple levels come into play it will need to have fully supported areas too to be able to build further.

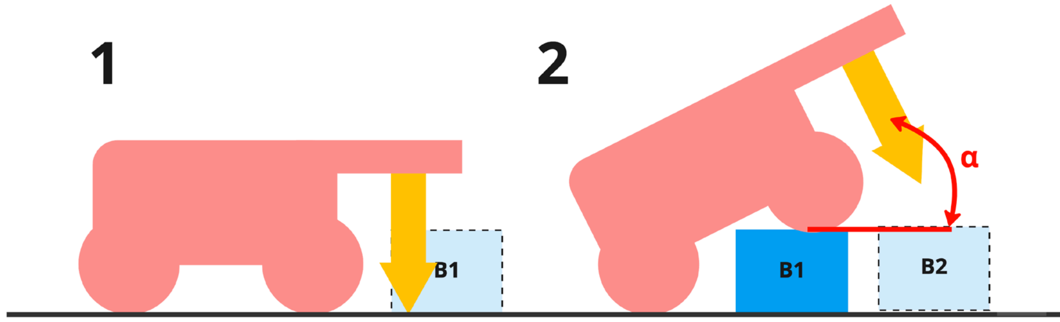


Figure 22: The builder needs to print while an angle alfa arose during the printing process.

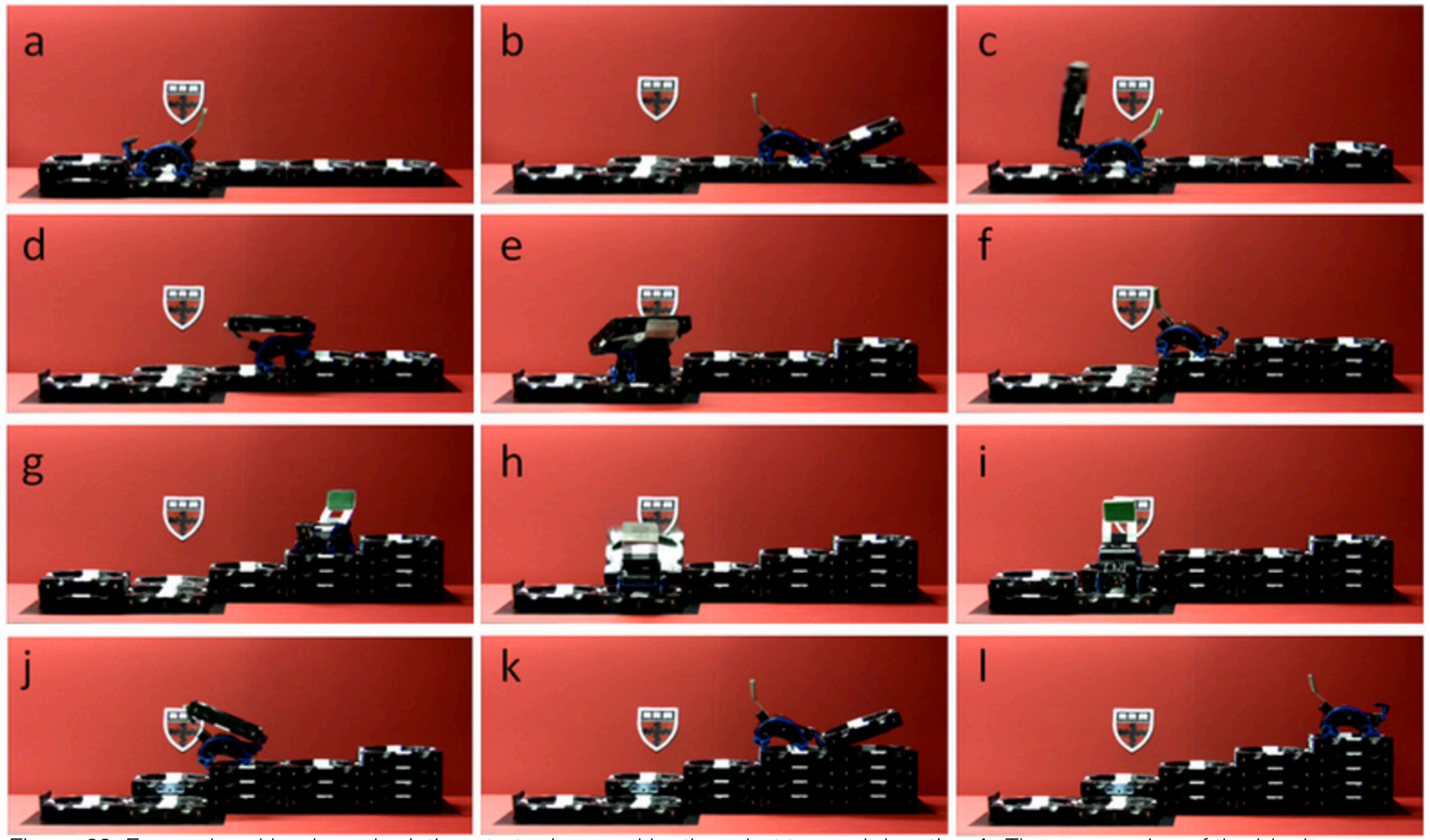


Figure 23: Forward and backward printing strategies used by the robot to reach location A. The sequencing of the blocks are numbered.

Continuous printing vs voxel system

'Continuous printing' refers to the process of printing entire structures in a single run. So imagine needing to build a ramp to point A in figure 20, the robot would then start printing the ramp as a whole. Looking back at how g-code and slicing software inherently works, one can quickly realize that continuous printing comes with many issues. The slicer always chooses to print the outline of the model first, which in this case means the robot needs a lot of space to move around. It would have a hard time printing that outline near the edge of obstacle A due to its body, unless some specific printing mechanism is employed. Furthermore, it also means that when it needs to print structures larger than itself, it would need to drive over the printed structures (in unfinished form). All in all, it seems that continuous printing brings a lot of risks and problems.

By dissecting the structures into smaller parts it helps in discretising the printing procedure. In this context, it translates to using pre-defined building blocks. Similar as the voxel system that was used in previous research (Biront, 2020), this repertoire of building blocks could be placed

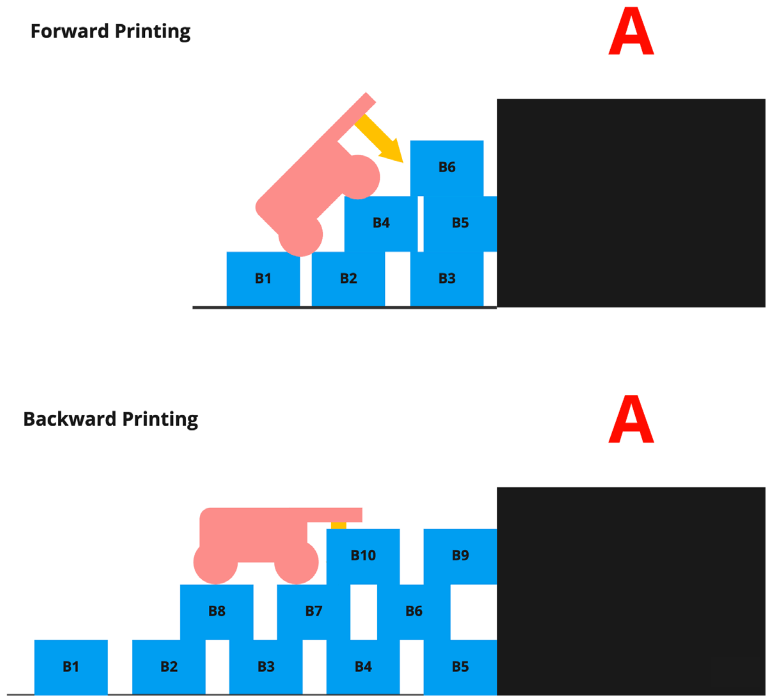


Figure 25: Forward and backward printing strategies used by the robot to reach location A. B1 means the first block it has printed, B2 the second one and so on. Here we see how backward printing needs extra 'length' on its layers to keep building.

in different ways. This method will also help reduce print time. What using voxels essentially does, is reducing the resolution of the structure and therefore reducing print time and material usage. By constraining the movement complexity by using simpler geometries such as rectangles, the 3D printer is able to move at higher speeds. In contrast to using more complicated geometries in which the printer may need to slow down to maintain print quality and accuracy. Different blocks can be added to the repertoire for specific goals, like a pre-defined ramp structure that can help in building in height in combination with 'regular' building blocks. Even certain landmarks/notches can be integrated to help localization of the system, similar to the Termes building blocks. For this assignment it was decided to keep the repertoire of building blocks out of the scope and use simple rectangles to gain the main benefits of this method. So whatever structure it needs to build, it will build that larger structure using its smaller rectangular building blocks.

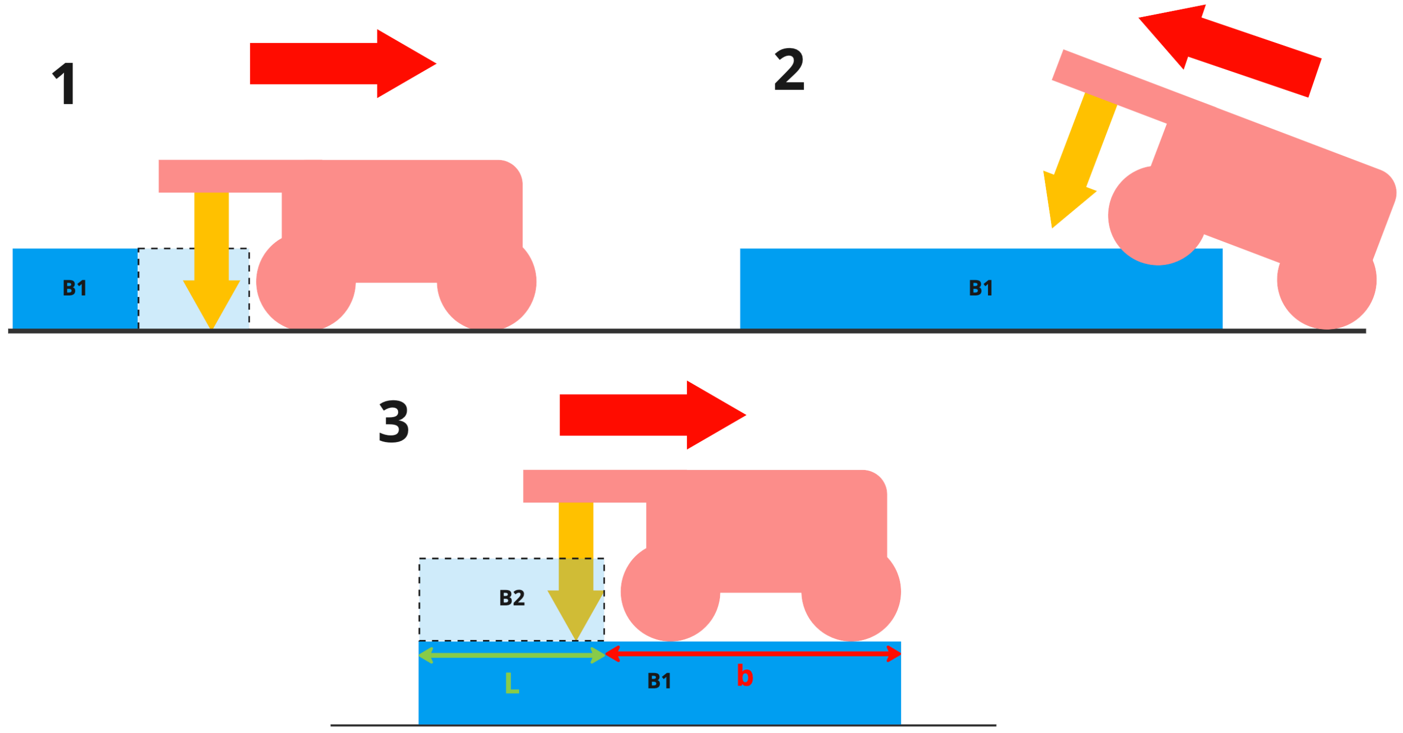


Figure 24: When printing backwards, it can simply print a long enough layer at each level to at least support itself fully

Continuous printing is not the same as what we refer to as 'dynamic printing'. Dynamic printing is defined as printing while simultaneously moving. So for instance when the robot does not have a print head that moves in a specific range, but the robot as a whole will move to replicate the motion required in the X and Y direction to print, similar to what the AMbots did.

Strategy summary

To summarize we have two printing strategies which is the forward printing and backward printing method. Both of these strategies will be employed for a voxel based printing system. The robot will build only using pre-defined rectangular blocks. Figure 25 illustrates both strategies being used to reach a location A at a certain height.

The forward printing method is able to reach location A using less blocks due to its ability to level itself and print at different levels. While the backward printing method relies on printing sufficient long layers for it to be able to fully support the robot. This avoids a leveling mechanism but decreases the efficiency of the system as a whole. Important is to realize that when you are able to print forward, printing backwards is also an option. That indicates that the forward printing strategy is generally more versatile than backward printing. FDM printers inherently require printing on surfaces at different heights to create 3D structures.In these scenarios we assumed that the printers were not able to print on top of another layer while being at the bottom layer. We simplified the robotic printers/builders to more easily grasp the possible tactics that can be used. A lot of these before mentioned issues could be overcome by adding more mechanisms to the system, but that is something that should be avoided. To make it a mobile and compact system, it should be kept simple.

List of requirements

Looking at the different building strategies and the goal of creating a robot builder that could be a part of a team in the future the following requirements were decided.

Performance requirements

1. **The robot must be able to print a simple rectangle structure using conventional techniques of FDM 3D printers**
2. **The robot must be able to climb a single layer of its own building block**
3. **The robot must be able to print directly on the ground (in a controlled environment)**
4. **he robot must be able to print on top of its own structure**
5. **The robot must be able to maneuver freely in the X-Y and rotate**
6. **Must have an accuracy of less than 100 um to be comparable with regular FDM 3D printers**
7. **Must be able to carry printing material**
8. **The robot must be able to print in the negative z-axis(below the surface it currently is resting on).**
9. **The robot must have a builder area with a width that is larger than its own width.**
10. **The robot must be able to traverse over the gaps left between building blocks**
11. **The robot must be balanced while climbing a single layer of its building block.**
12. **The robot must be able to build structures in somewhat different controlled environments (geometries).**
13. **The robot must be able to reproduce the building block with a minimum of 90% dimensional accuracy, meaning if the block is meant to be 10 mm wide it should reproduce a block that is between 9-11 mm. This to avoid having to print much larger and especially wider voxels than necessary.**

Product costs

1. The robot must be able to be build with costs being under €1000,-

Size and weight

1. The robot's footprint must be no longer than a standard laptop.
2. The robot must be lightweight enough for its 3D printed structures to support it fully.

Wishes

1. The robot can print structures 50% as fast as basic 3D printers such as the Ender 3.
2. The robot can print ~20 blocks without needing to refill or readjust.
3. The robot can function for ~10 hours without any critical failures.

Morphological Chart Brainstorm

With the requirements in mind, sub-functions of the system were defined to be able to create a morphological chart. The sub-functions are:

1. XYZ-control
2. Locomotion
3. Building Strategy
4. Leveling the system

In this case it is important to know that sub-function 4: Leveling the system is obviously only applicable when the forward printing strategy is chosen. The "XYZ-control' implies the 3D printing system. Locomotion is the system used to traverse around and climb.

Leveling the system

For the solution space of leveling the system to overcome the angle issue, different kinds of mechanisms were thought of to help the builder during the climbing. The first idea was to actuate both of the wheel axles. This meant that it the axles could move up and down which could level the robot. It also meant that the z-motion during the printing could be done by these actuated axles(See figure 26 here below). The same could be done by only actuating one axle, another stepper motor for the z-motion of the printhead must still be added then.

To even reduce the complexity more it was also an interesting idea to make the robot fit on one of its building blocks(figure 27). This meant that it could always level out after it placed its block. The biggest challenge with this idea are the dimensions needed to make this possible. It has to be a very compact system or you have to print large blocks.

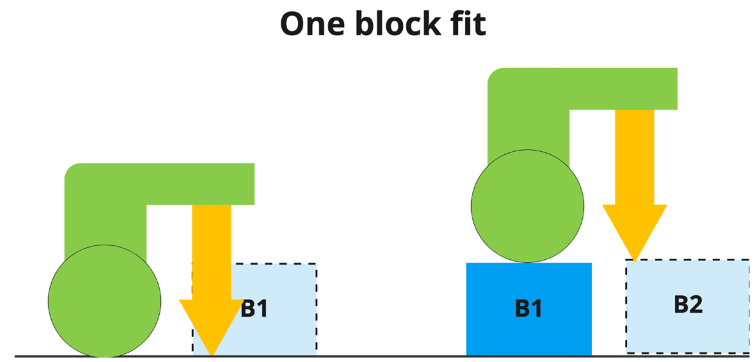


Figure 27: the simplest solution, designing a robot that fits on a single block.

Another idea was to not level the whole robot but to place an actuator that could rotate the print head. So the moment it is angled you can simply activate the actuator and level the print head with the surface(figure 28). This seems rather simple, but the challenge can be found in having to move the whole printing mechanism in a precise manner. Rigidity already is an important factor that needs attention, when adding more mechanisms to the nozzle it increase the risk of failure.

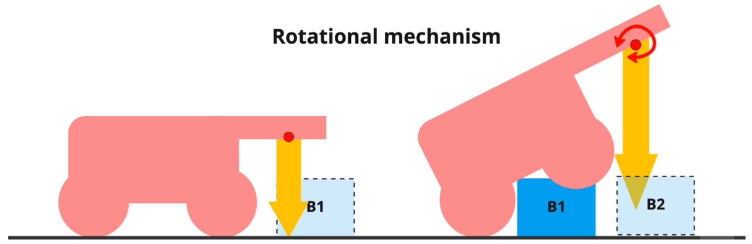


Figure 28: A rotational mechanism implemented in the printhead, technically it should level faster due to reducing the mass that needs to move.

Various kinds of solutions were found by doing short brainstorm sessions per sub- function. Then all of the solutions were inserted into the morphological chart. Using the chart various kinds of concepts for the robotic build-

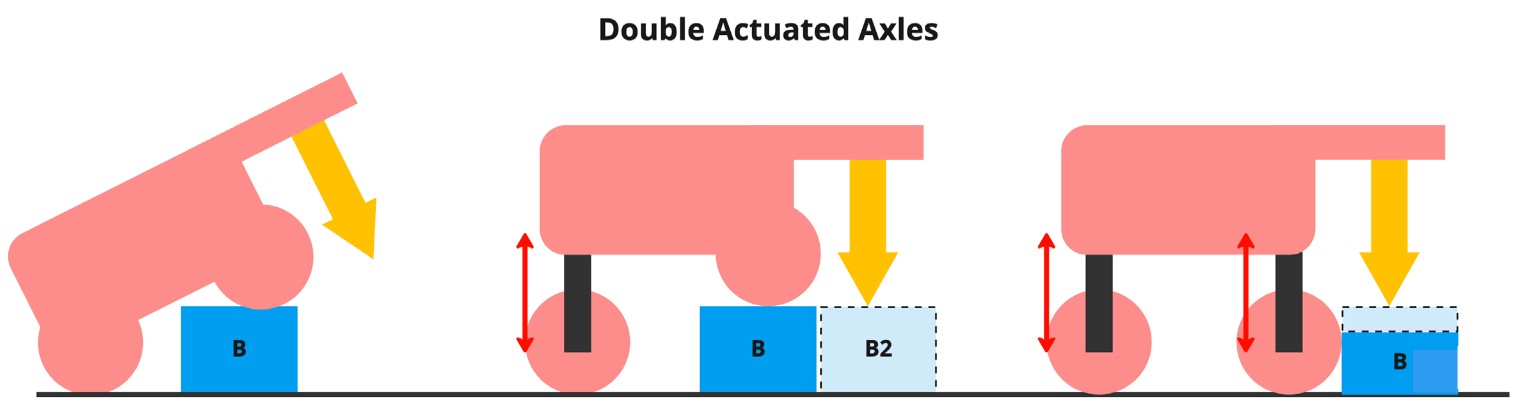


Figure 26: The double actuated axles can also effectively function as the stepper motor in the z-direction.

er were created. Due to the open ended nature of this project this brainstorm was done with the aim to get an idea of how the system could look like. For each of these solution combinations a sketch was made. Some points of the brainchart session can be found in figure 29.

The morphological chart did have some issues in regards to overlapping and conditional solutions. For instance, the dynamic printing system essentially locks in the mecanum wheels solution if we are being realistic. While the backward printing strategy totally avoids the leveling solutions. And with some of the solutions such as robot legs, it became quite apparent during sketching that it was not as viable or feasible. So some of the solutions and combinations have been avoided. The chart was a good way of quickly visualising the proposed builder and disregarding the 'bad' ideas.

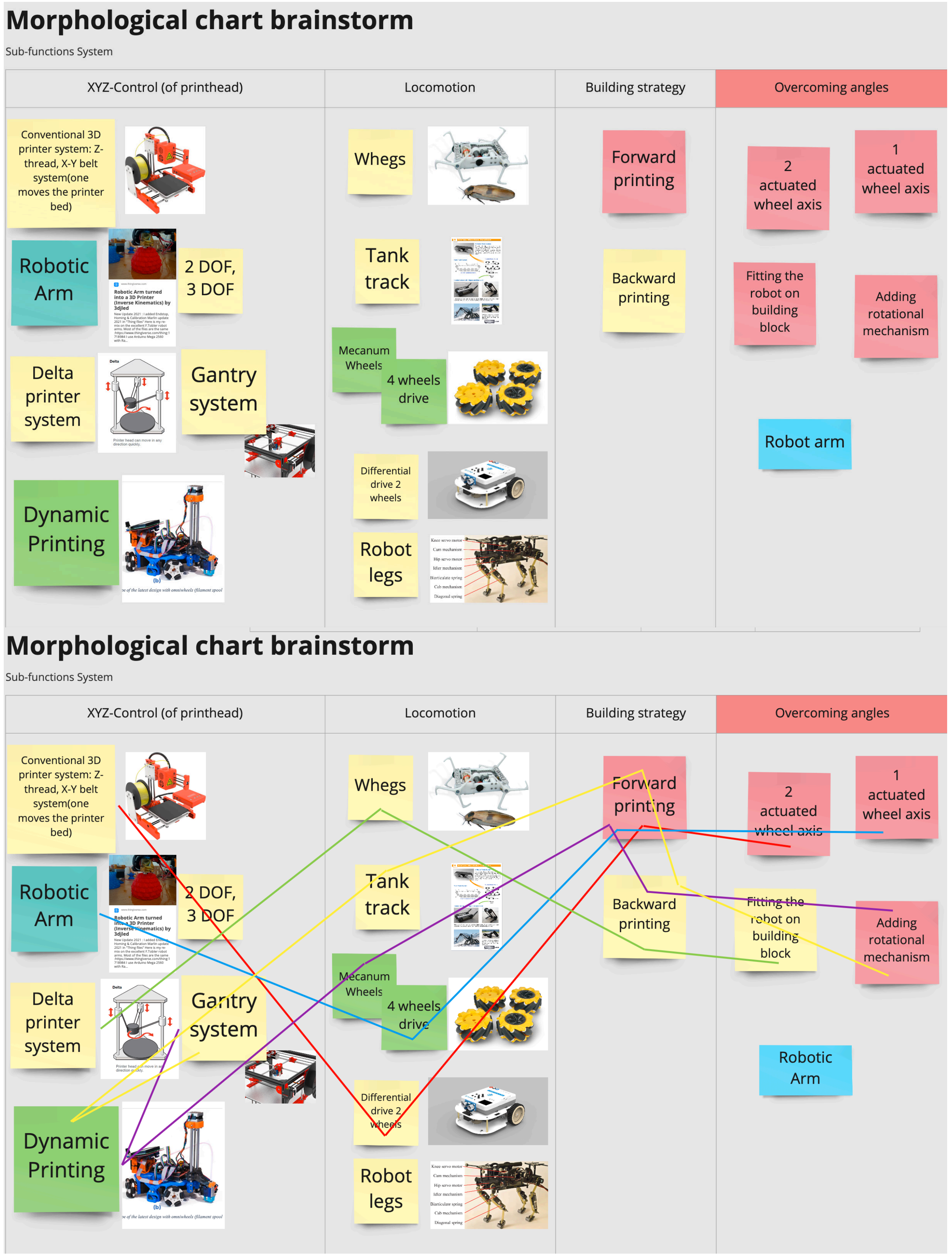


Figure 29: Screenshots of the morphological chart brainstorm session at different time points.

Concepts Visualisation

To be able to evaluate the different concepts, sketches were made and requirements for a Harris Profile were defined. The Harris Profile method was chosen due to simple setup and its easy to follow visual representation of the evaluation. As the sketches do not go in great detail, the Harris Profile is great tool to get a quick and dirty evaluation of concepts. The requirements that were chosen for the HP were (in specific order):

1. Printing
Here we rate the printing capabilities on various factors. Looking at things such as the build area, the weight and size of the printer section. Factors such as printing speed and accuracy are hard to judge or estimate at this point in the process.

2. Locomotion
We look at the various methods of moving around and how effective it is. The effectiveness can be judged by its turning radius and the capability to move around on rougher terrain for example.

3. Feasibility
Very complex and intricate systems have more chance of failing. It becomes less feasible for this particular project and its timeframe but also in general for future work. We want to design a system that has the potential to be used in a swarm robotic fleet for construction. Obviously at this stage the design would be a proof of concept, but it is important to be critical about the future.

4. Climbing
The better rated, the better the climbing capabilities of the design. When a system is able to climb steadily thus with no or low risk of tipping over for example, only then should we look into the other details.

5. Adaptability
We are looking to create swarm robots that are able to help construction on various terrains that can be difficult for humans to reach. Adaptability rates the concepts on how it would perform in areas where the geometry may not be that consistent. How can it move itself and or the printer around? Does it have different ways of building structures?

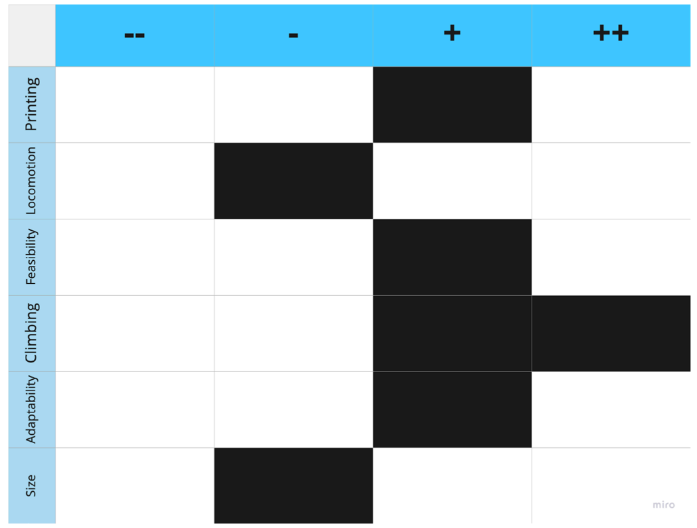
6. Size
This system can help in areas that may be protected, environmentally or even historically. We want to maintain a system size that is similar to that of a laptop. This also reduces the chance of weight issues when climbing printed structures.

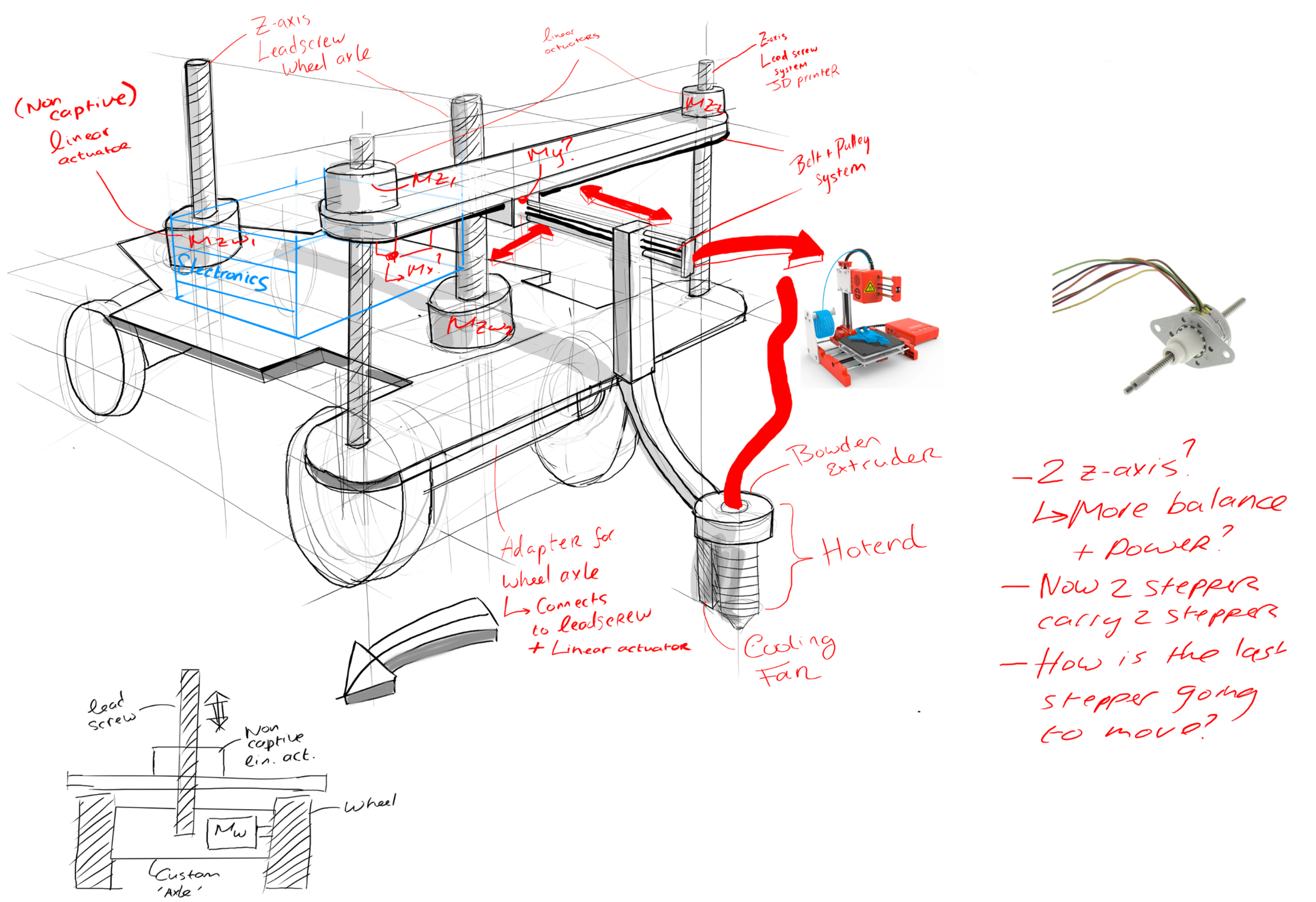
With Harris Profiles the order of the requirements matter, the most important requirement can be found at the top of the HP. All of the requirements will then be judged, using --, -, + and ++. These signs obviously indicate in how well they concepts perform in these requirements. Important to note is that in the Harris Profile Method there is no neutral choice in the assessment, this forces the designer to evaluate the concept harsher and place it in the bad(-) or good(+) position. This helps the to make a more definitive choice.

Concept 1

Concept 1 uses the double axles system to overcome the angling issue. In this concept two linear actuators are directly connected to the wheel axles. These actuators can then drive the axles up and down which can level the robot but also be the main driver of the z motion during printing by moving both axles simultaneously. The X and Y movement in the print head are accomplished by a gantry-like mechanism. The first link is a component that is placed on a ‘bridge’ between two poles. The component is attached to a rail on the ‘bridge’, it can move up and down the X-axis using belts. The component extends to another rail that is supposed to house the Y motion. On this rail that protrudes from the bridge to the front of the robot, is the final hot-end holder which also is able to move around using belts.

This concept’s climbing capabilities has potential, the actuated axles in combination with (large enough) wheels is interesting. Whegs would also be a viable option for this concept. However, the size and locomotion are its weakest points caused by the gantry system and a non optimised differential drive system. To fully utilise a differential driven system the back wheels should have been replaced by one wheel or a smooth support.

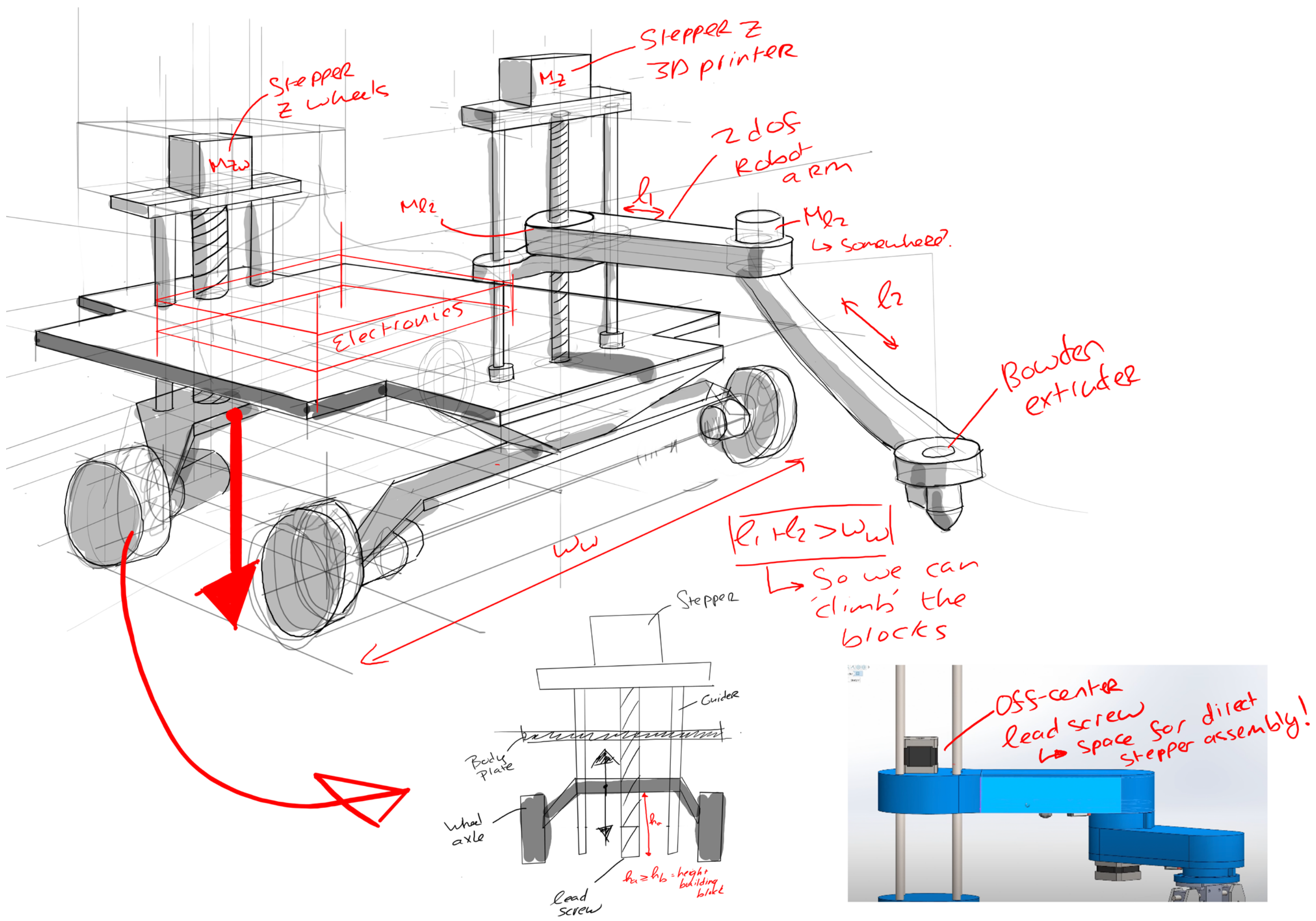




Concept 2

This concept uses a 3 DOF robotic arm as the print nozzle. It removes one of the driven axles leaving only the back axle to be able to move up and down. The strongest points of this concept are its printing capabilities, feasibility and size all of which gain significant benefits from using a robotic arm. These SCARA type robotic arms creates an effective compact system that is versatile without adding too much complexity. However, the challenge in using a robotic arm lies on the software side of things. The movement of a simple 4 wheel drive system is limited.

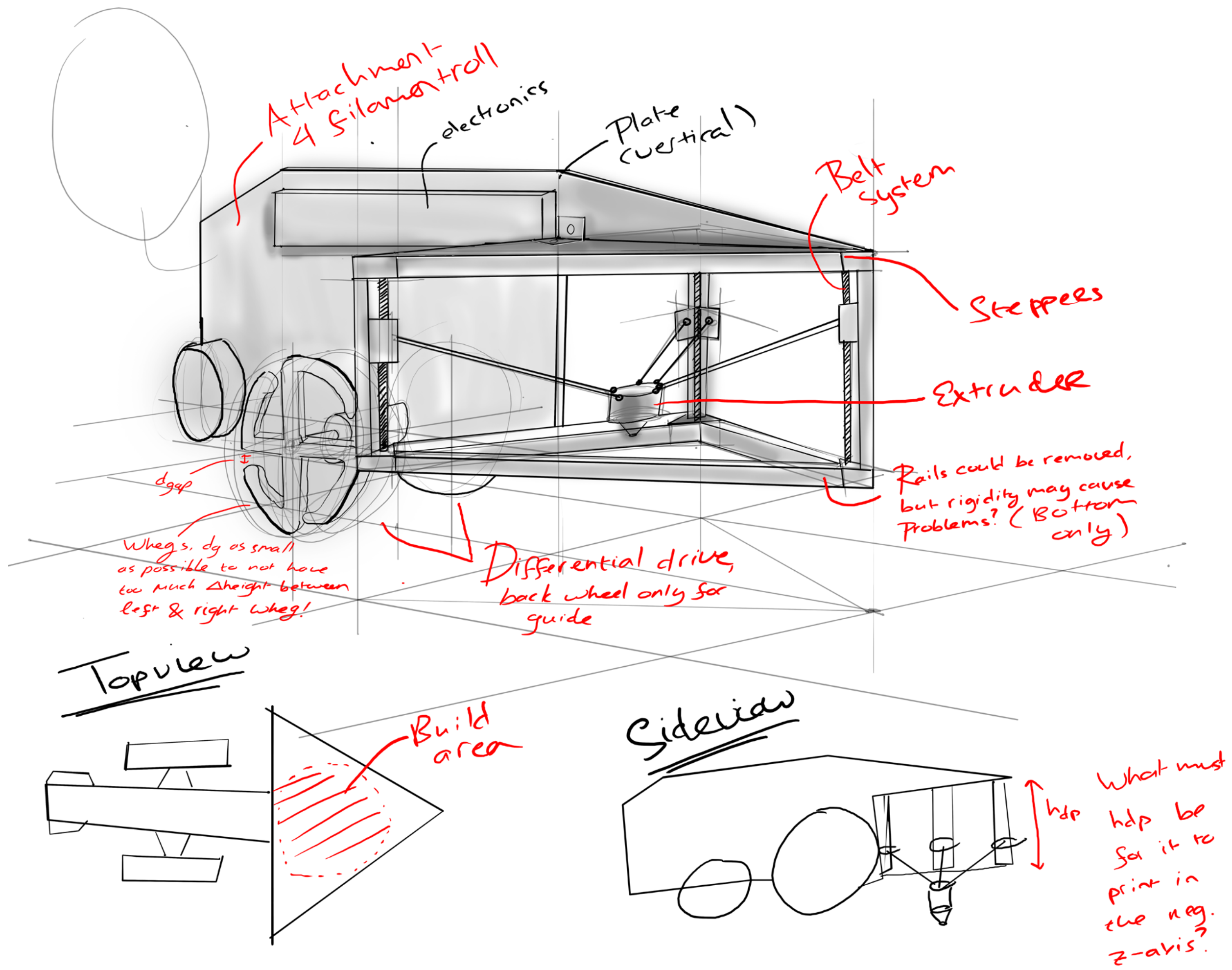
	--	-	+	++
Printing			■	■
Locomotion	■	■		
Feasibility			■	■
Climbing			■	
Adaptability			■	
Size			■	■



Concept 3

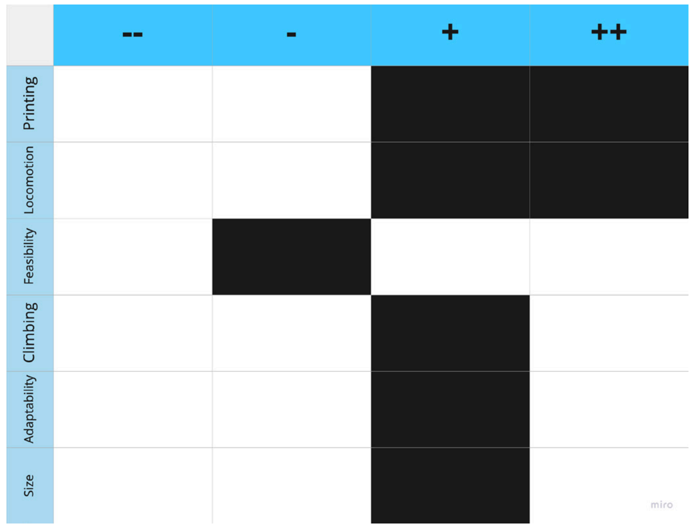
The third concept focused on using the same printing setup as a delta printer. A delta 3D printer uses three vertical arms to move the print head in a triangular motion, allowing for fast and accurate printing of large, intricate objects. A triangular frame holds these vertical arms and it utilises a vertical placed plate as its ‘body’ and a differential drive system. The build area of this concept is bounded by its triangular frame on the front, which means that to increase the build area the delta printer frame must be huge. The differential drive system improves its mobility while being more compact. This delta printer based system must be quite large and has many complex moving parts. It is also supposed to be able to stand on one block for it to function properly, which seems unattainable given the restriction of its frame relative to its build space.

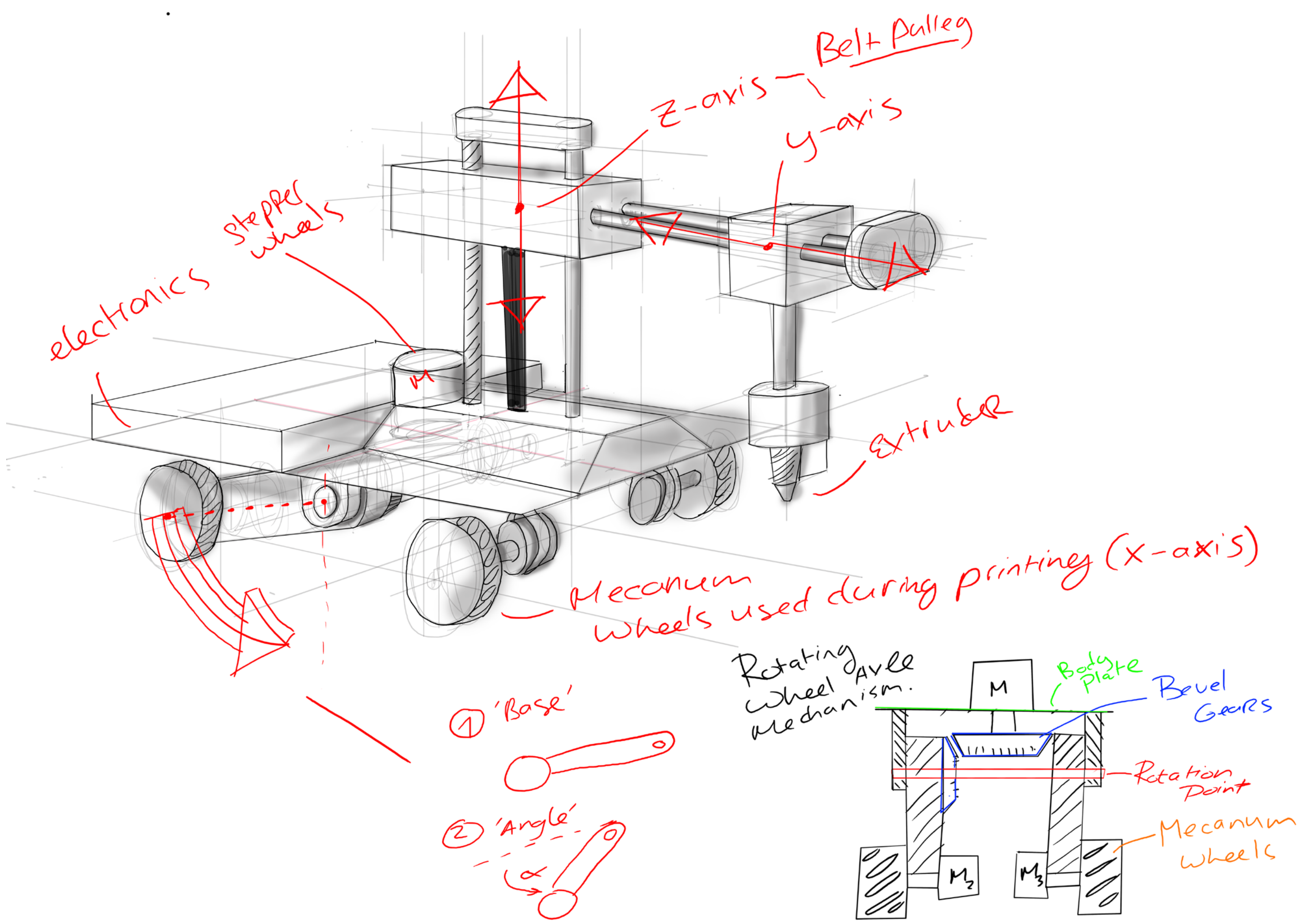
	--	-	+	++
Printing	■	■		
Locomotion			■	■
Feasibility	■	■		
Climbing			■	
Adaptability	■	■		
Size	■	■		



Concept 4

Concept 4 focuses on continuous printing while using a simple rotation mechanism to compensate for the angles. Instead of rotating the print head which meant adding weight to the nozzle, it seemed a more refined solution to add the rotation mechanism to the wheel axle again. It is similar to what a suspension system in a car does, only it is actively actuated instead of passively. Using mecanum wheels mean the system can freely move in any direction, and that movement can be used for the X and Y motion while printing. In this case, only the X-axis motion is replaced by the wheels. The idea was to minimize the risk of large errors due to wheel slippage by replacing only one direction of the motion In theory it can also print infinite long structures, however this won't work with the voxel system. By using the mecanum wheels while printing the system can be more compact, but it also means that it needs extra space to print properly. When its printing on a layer above the ground, it will fall off when trying to print a structure as wide as it self if the layer its standing on is not wide enough. This fatal error means the system needs to print marginally larger areas as it is building structures in height or it will simply fall of and fail.





Conclusion

It seems that employing a SCARA like robotic arm can bring many benefits. The size, weight and versatility are some of the factors that makes it such an attractive option. The biggest down side of using a robotic arm setup resides in the firmware which is a large knowledge gap. Regarding the locomotion of the system we can find several good options that also are not exclusive from each other. Interesting would be to combine the whegs design with a differential drive system and the other option would be to use mecanum wheels. In this context, 'dynamic' printing should be avoided, even when it uses a voxel system. The inaccuracies that it brings by slipping can become larger marginal errors over time and it will be necessary to an open loop feedback system of some sorts which adds unnecessary layers. Adding at least one actuated axle to be able to level the builder is a simple yet effective solution for the leveling. Having the robot fit on one block is interesting but the feasibility of it is a big challenge.

Improvements

The morphological chart was not used optimally in this brainstorm session. There were still a lot of unknowns at the start of the brainstorm which caused the morphological chart to have many solutions that ended up being not feasible or solutions that got in the way of each other. For example, the forward and backward printing strategies were in most cases not a useful solution to have in the chart as many of the ideas were able to do both. That is also the reason why not all solutions were used and that some concepts had to avoid a specific column to not interfere with a solution from another column. It is important to understand that the chart was mainly used to get an better understanding of the robots potential embodiment design.

4 Design

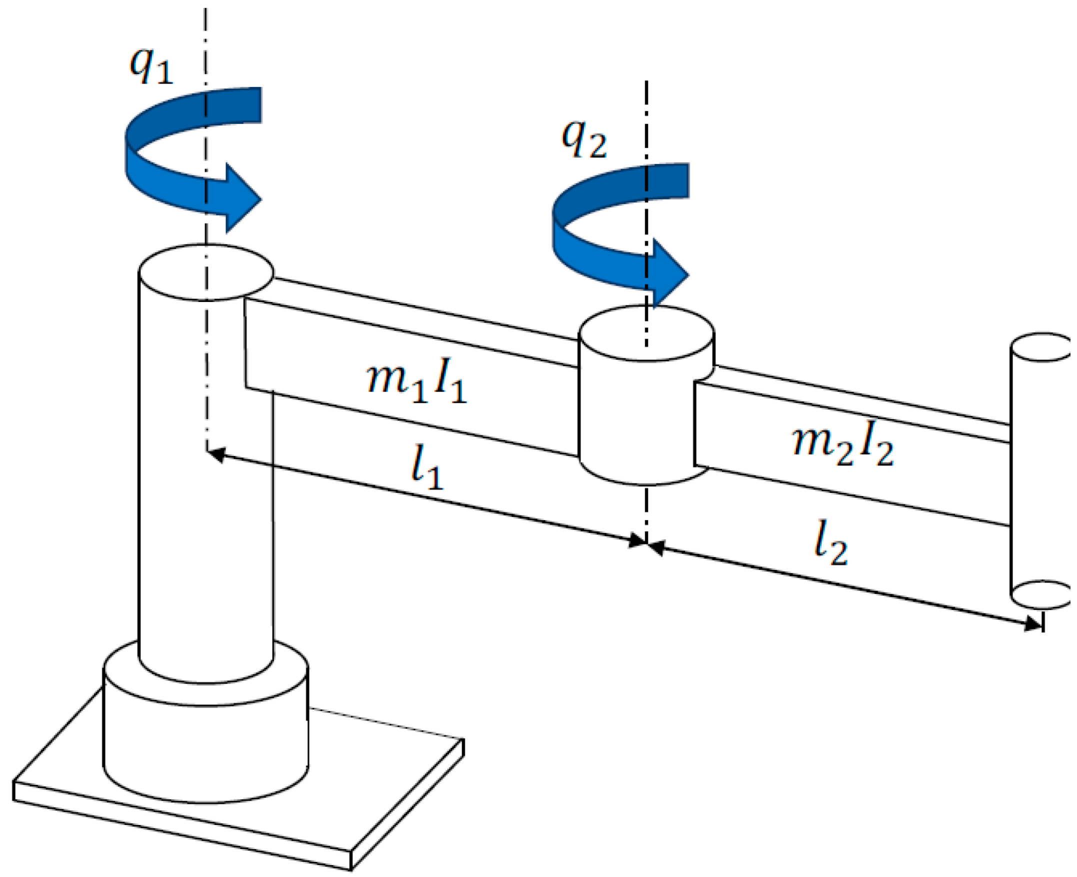


Figure 30: A simple rendition of a two-DOF SCARA robot with its joints and links retrieved from Soriano (2021).

SCARA Arm

In the end it was determined that concept 2, that came from the morphological chart, has the best potential out of all the concepts. The most important asset of concept 2 was the SCARA arm that replaces the conventional gantry-like systems of printers. The SCARA arm adds a lot of range to the system without being bulky, it also uses a relative simple mechanism for a robotic arm resulting it to be lightweight. If you look at figure xxx here above, you see that a SCARA arm consists of two links and two joints. In this case we call joint q1 the shoulder joint and q2 the elbow joint. Link l1 will become the shoulder link and l2 the elbow link. The arm is able to move around in 2D space by only rotating the two joints, in theory it can reach any location within a radius of the sum of elbow and shoulder link lengths.

To be able to further develop this SCARA arm, calculations necessary to get an idea of the required dimensions.

Dimensions

In order to determine the required dimensions for the system, a Matlab code was used to plot all the obtainable coordinates of the SCARA arm based on its length and joint range. The code finds the largest distance between any two sequential points in the plot to find the accuracy/resolution of the system(see figure 31). The gear reduction ratio, arm lengths and microstepping size are the variables that could be inserted into the code. The shoulder was limited to a rotation of -90 to 90 degrees wherein 0 degrees meant that the arm was dead center in the middle. The first step was to look at the ratio of the arm lengths (elbow and shoulder) and how it affected the overal build area of the SCARA arm. Giving the system three options.

1. L1>L2
2. L1=L2
3. L1<L2

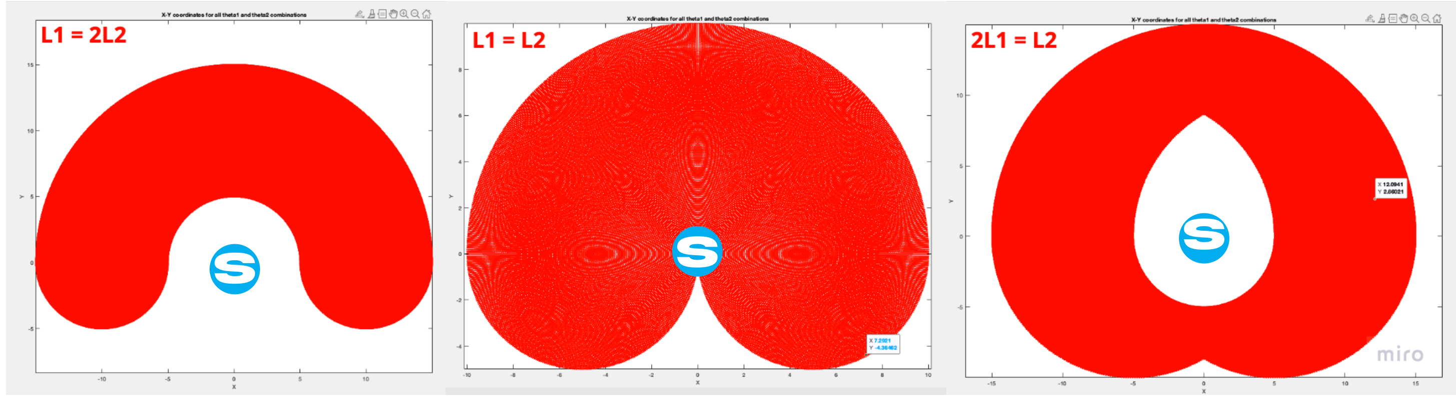


Figure 32: Plots of all the possible coordinates of the SCARA arm using different ratios for the links. Wherein L1 = length of shoulder link, L2 = length of elbow link and S = coordinates of the shoulder joint (base).

Wherein L1 = shoulder arm length and L2 = elbow arm length. The plotted results can be seen in figure 32 here above.

Having identical arm lengths creates the largest build area where the arm can reach most orientations in front of itself. While the other length ratios creates gaps in its build area as seen in the plots here above.

Important to note here is that the above plot does not consider the fact that such a SCARA arm has to operate in a right handed system (RHS) or left handed system (LHS). That simply means limiting the links so that the elbow is always placed on the left or right hand side from the links, at most it will be in-line with the links when the arm is fully stretched out. Consequently, the build plate dimensions will be smaller in practice than the projected ones here above to avoid rather sudden huge movements during printing.

Accuracy

The requirement was to reach a resolution of at least 100 microns. The resolution is affected by the gear reduction ratio, microstepping size and length and ratio of the arms. It was more desired to use a simple single stage gear reduction system while using GT2 pulleys. In this case we went with a jump from 20 to 60 teeth creating a reduction ratio of 1:3.

Microstepping is an essential technique for improving the resolution and smoothness of 3D printing (Robinson, 2019). Each “step” that the printer takes is divided into smaller, more exact “microsteps” to accomplish its task. This also helps in getting improved print quality and reducing noise from the steppers. Employing microstepping can help the printer move more smoothly and prevent jerky or uneven movement. The downsides of this technique is that it reduces the overal torque and speed of the stepper motors. The added steps can also cause more produced heat and requires more computational power. Good to note is that microstepping means the resolution increases but the accuracy of the stepper motors stays the same. Meaning that decreasing

```
ratio =

     3

microstep_a =

    0.0625

resolution_microns =

   65.4567

arm_lengths_mm =

   100   100
```

Figure 32: Output of the matlab code.

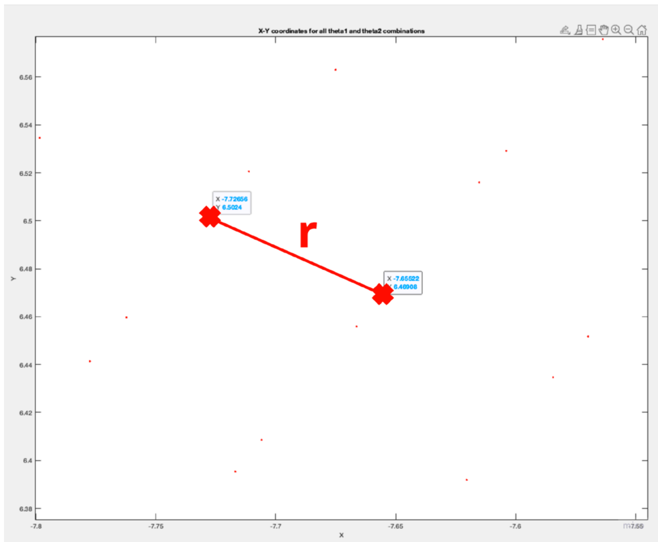


Figure 31: Matlab plot of two sequential coordinates with the largest difference between them.

the step size by too much causes step skipping. The most common step size for 3D printers is the 1/16 microstep which supported by most stepper drivers. This will be the step size that we will use.

For the length of the arms the requirement for the overall size and footprint was taken into consideration, ultimately it was decided to use 100 mm length per link. When adding these 3 variables together, being the reduction ratio, step size and link lengths the Matlab code calculates an estimated resolution of ~65 microns(see figure 32).

Using the Matlab code and its plot an estimate of the build area can be deducted. Which in the case of 100 mm long arms will be roughly ~450 cm^2. The maximum width of its build area ends up being ~300 mm. This gives us a good margin to be able to print wide enough structures for the robot to stand on.

Concept Brainstorm

To finalise the design of the SCARA arm inspiration was taken from many different types of SCARA designs found online and in papers. The 3 main inspirations for the designs were the open source Arduino Scara Robot by Klusáček(2019), the open source X-SCARA project designed by Mircescu(2021) and the AMbots swarm printer as previously mentioned in the research chapter (see figure 33).

With these references 3 designs were modeled in a CAD program to get a better understanding of how the overall mechanism would look like with the requirements. Each design had a different focus point. In general the system consists of 3 components.

1. The Base Tower
The base will house the lead screw that will take care of the movement in z- direction. The base will also be the main attachment point to the future mobile hub and house most of the electronics. Several guide rods are installed to help with alignment and smooth movement.

2. The Shoulder Link
The shoulder joint will be placed near the base and be limited to move from -90 to 90 degrees. The shoulder link will house the belt and pulley systems.

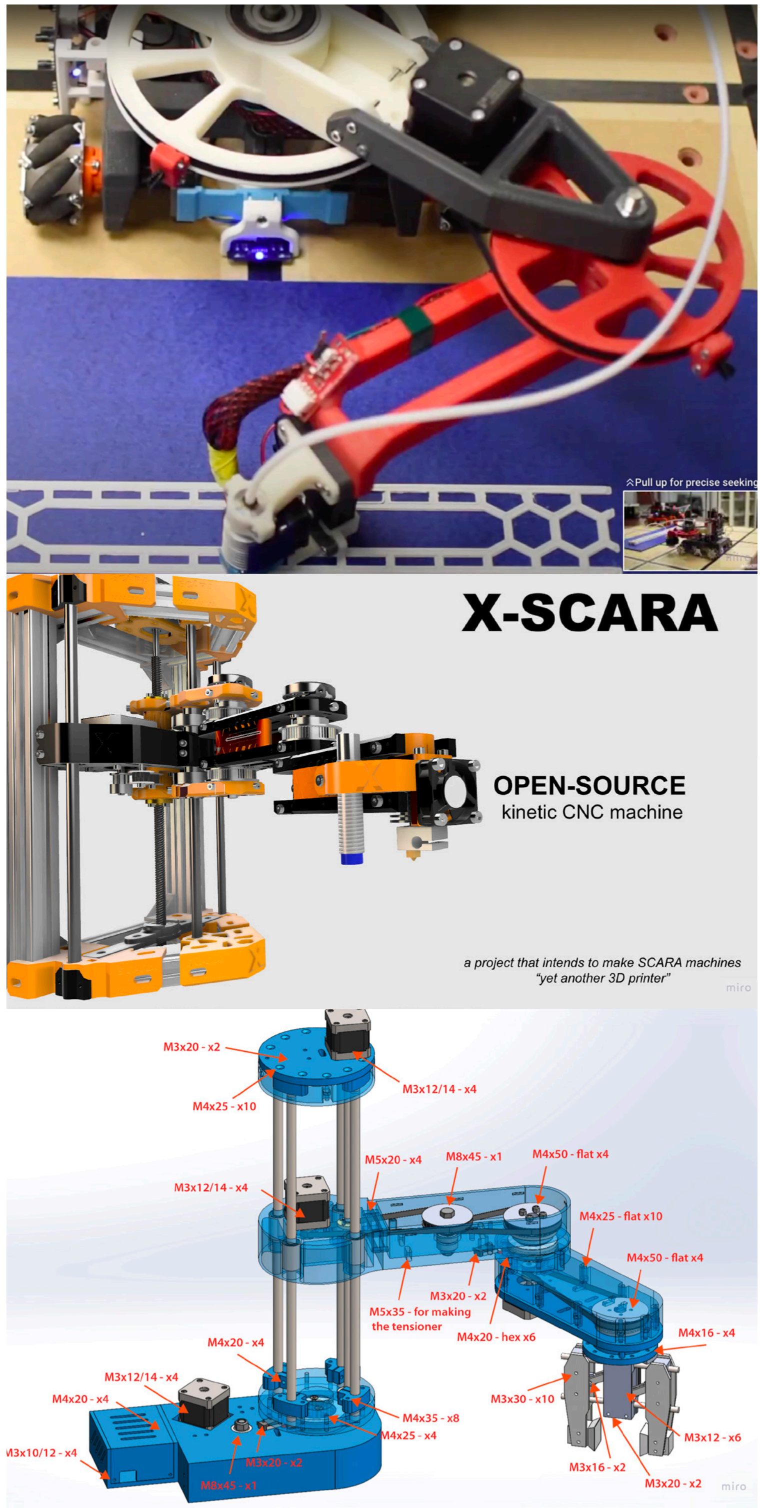


Figure 33: From top to bottom; AMbots Swarm Printer, X-SCARA machine and the Arduino Scara Robot.

3. The Elbow Link
The elbow arm will be the component that will hold the hot-end of the printer. This end will hold weight while being the lightest component, the elbow is a potential point of failure.

Design #1: The Lightweight (figure 33)
The first design uses a two stage gear reduction systems to be able to place all three steppers (X, Y and Z) onto the base plate. This creates a lightweight arm that is under minimal stress. The pulley that drives the elbow is placed on top of the shoulder joint. The elbow pulley is placed in such a way that it is squeezed between two bearings, and it is able to freely rotate on the smooth rod. You can see the pink pulley in the figure 34 here to the right, where it only touches the bearings. This setup means that the shoulder joint can rotate without affecting the elbow joint. The base uses two plates that clamps down onto the shoulder joint. This setup was chosen to improve alignment of the guide rods and z-rod , but also to fortify the rigidity of the shoulder joint by using clamping force. The Z stepper is placed on top of the base structure where it drives the lead screw through the 2 base plates.

Making the arms as light as possible should increase the speed and power efficiency of the system, but it also means that a lot of rigidity is lost. The weight of the off the shelf hot-end, or even the forces of the tightened belt could in theory easily flex the arm. This will trigger major issues while 3D printing.

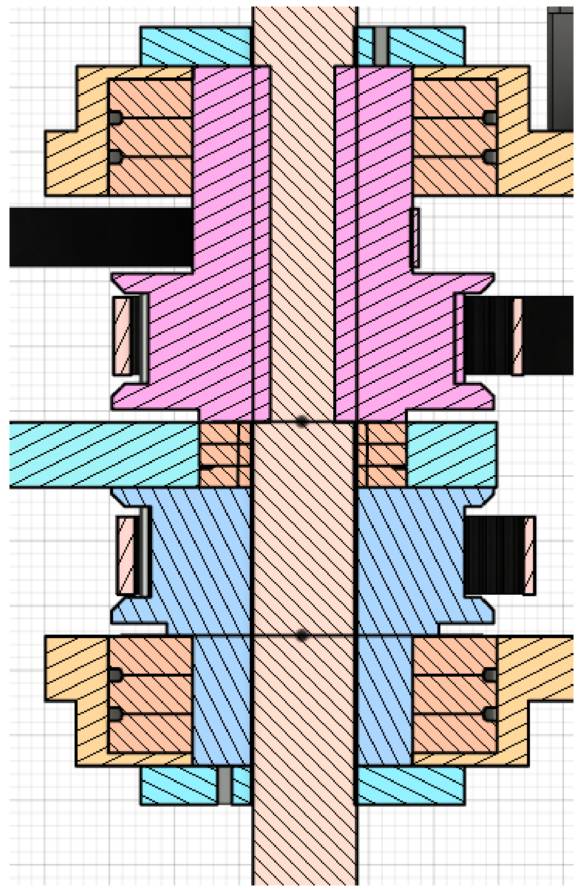


Figure 34: Dissected view of shoulder joint where the pink pulley is free rotating.

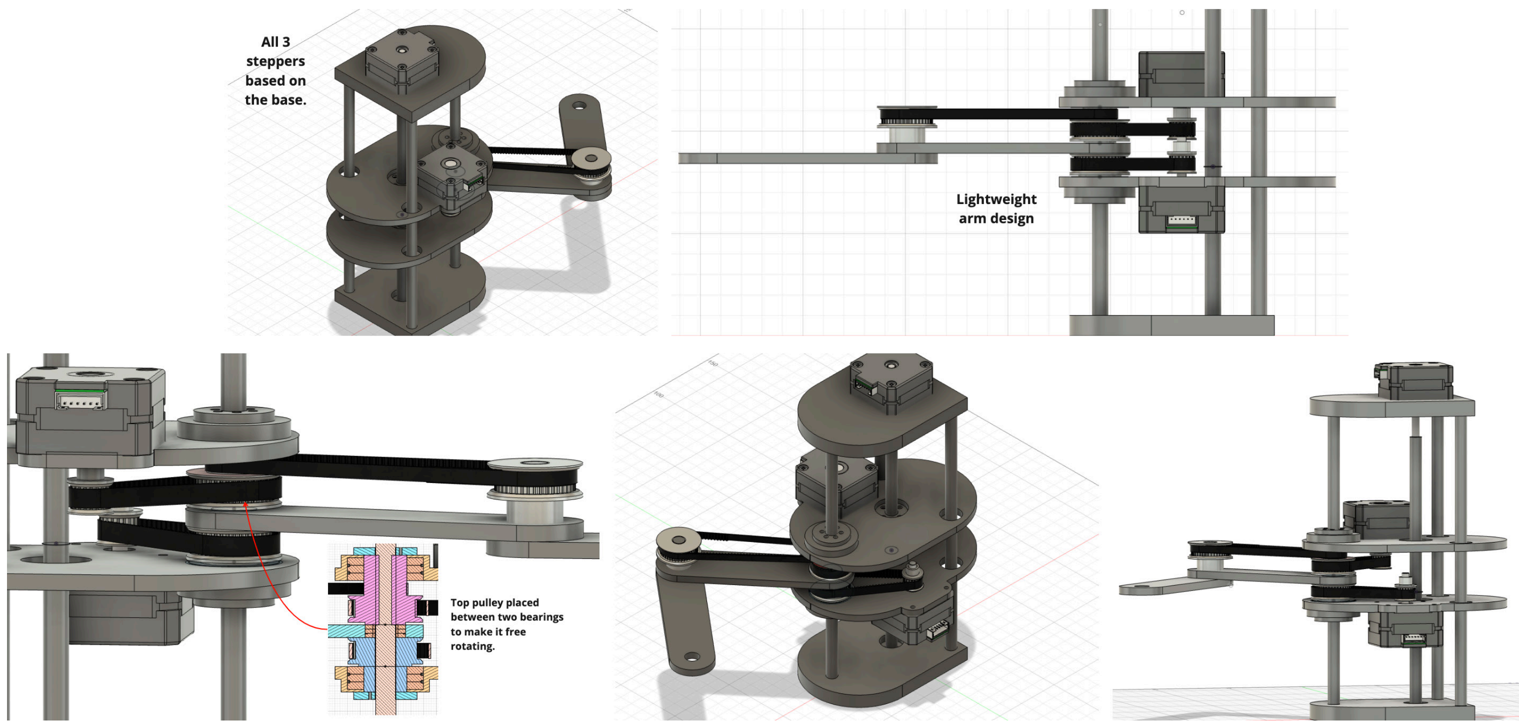


Figure 33: Various views of "The lightweight" concept design.

Design #2: KISS (figure 35)

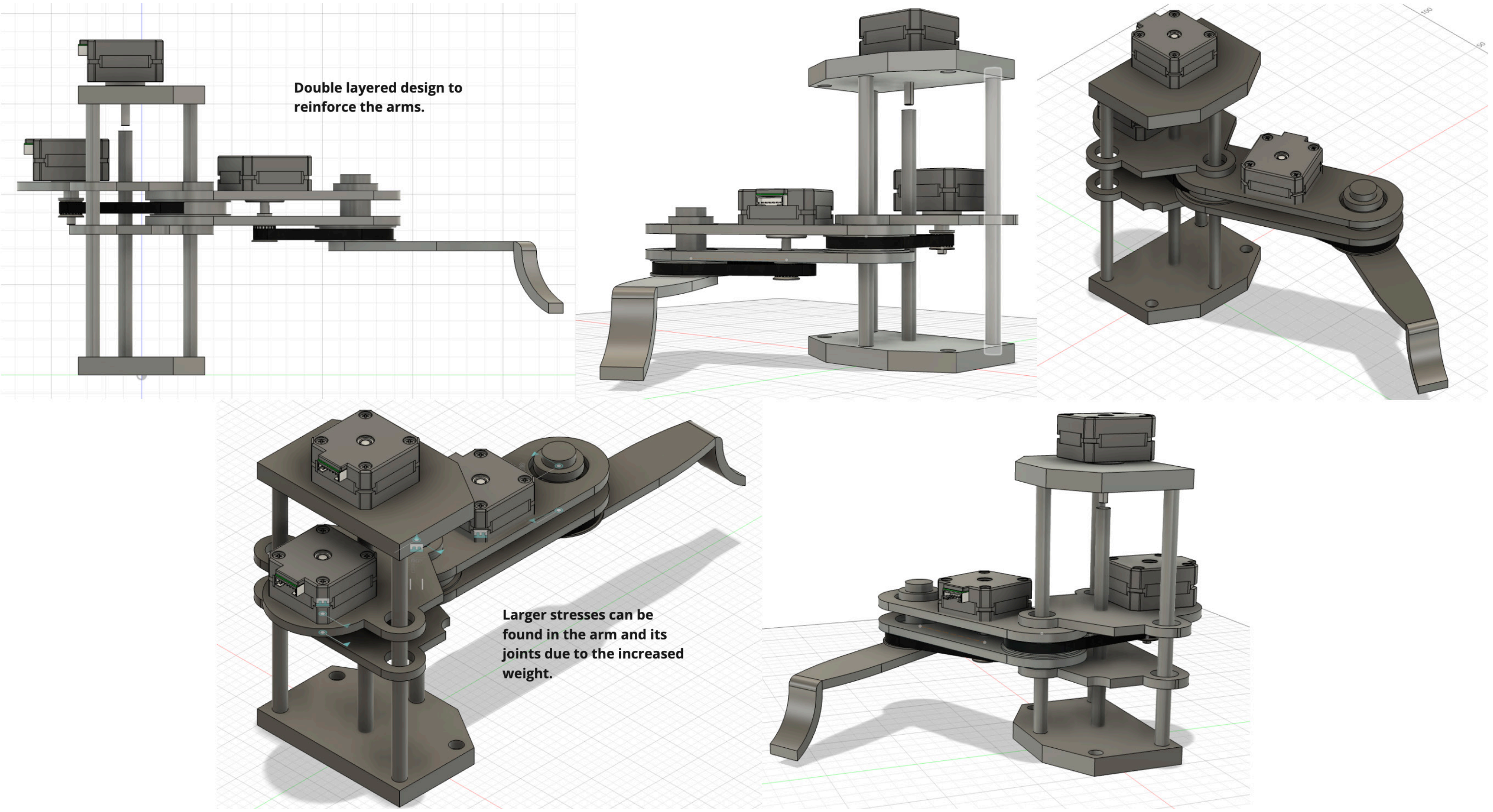


Figure 35: Various views of “KISS” concept design.

The second design uses a more straight forward way of implementing the SCARA arm. In this design the stepper that drives the elbow link is directly placed on top of the shoulder link near the joint to simplify the kinematics of the system. As the previous system, this means that the shoulder can operate freely without affecting the angle of the elbow relative to the absolute x-axis. One of the downsides of this design is that weight is added to the arm and stress in the joints increases. It also means that the steppers will need more torque and power in general to drive the links. The estimated weight of a regular nema 17 stepper motor is ~250 grams. In this design a pancake nema 17 stepper was used for the elbow joint reducing the weight to ~130 grams. Finally a double plated design is implemented for the shoulder link, similar to baseplate design that clamps down on the shoulder joint. This design reinforces the arm and therefore the end effector in some capacity. It uses a single stage belt and pulley reduction system for both joints.

The KISS design (as the name indicates) focuses on a simple and bare bones design, avoiding an over engineered design. Less complex mechanism means less points of failure and a more forgiving build process. The trade off can be found in the precision, accuracy and reliability.

Design #3: Tall Arm (figure 36)

The third design also places the stepper the drives the elbow on the shoulder link, but rather than on the joint it is positioned above the baseplates to minimize the stress. To reduce the points of failure, this design attaches the stepper motor directly to the shoulder joint, no belts and pulleys are used. Which also means that no gear reduction system is used and that therefore the step size must be adjusted to keep the same resolution. On top of that it is important to note that this also means that the torque output of the stepper is reduced. But seeing that the other designs use a relative small gear reduction ratio, this shouldn’t be a major problem. The system is less compact in the z-axis because of the vertical alignment of the elbow and shoulder stepper motors.

In general, this design focuses on minimizing stresses and deformation. These potential threats could cause major issues while 3D printing, underscoring the importance of focusing on them. It may be a worthwhile trade off to prioritize on rigidity and sturdiness and have a less compact system.

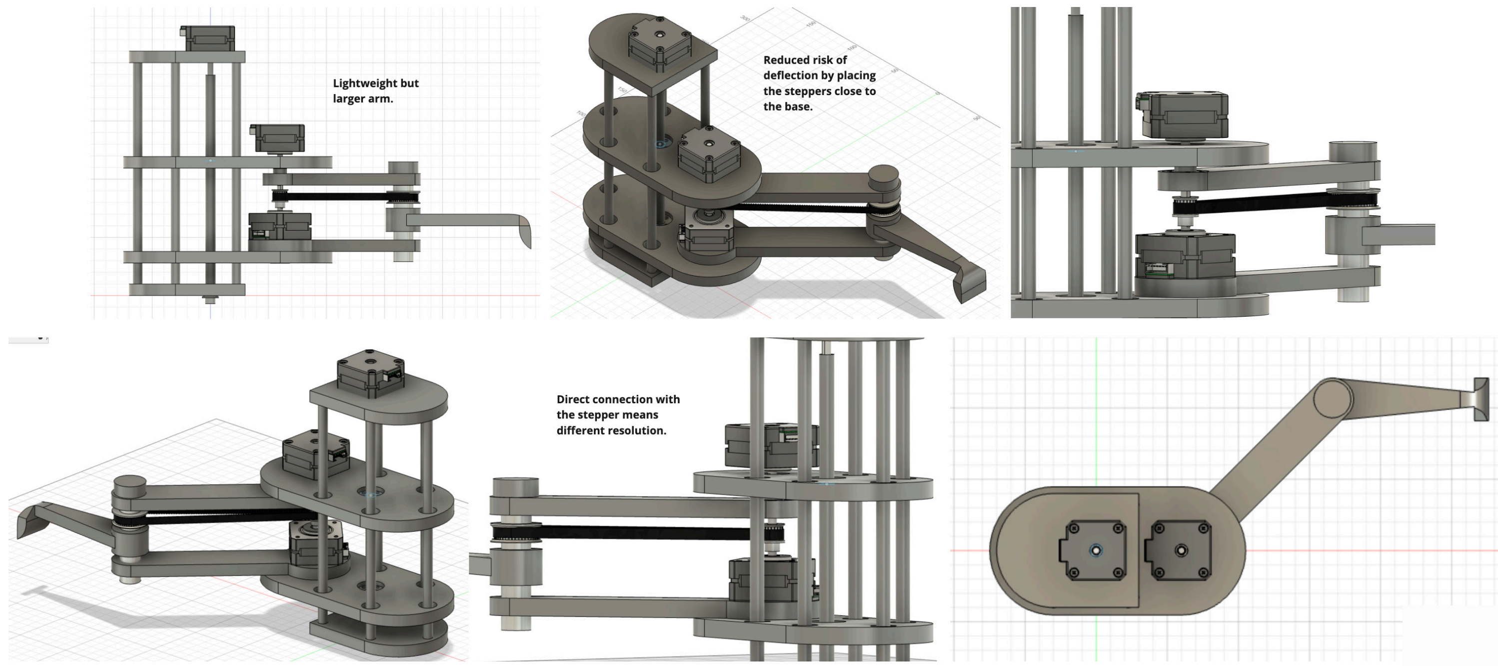


Figure 36: Various views of “The lightweight” concept design.

Conclusion

It was finally decided to use design 2 as the base model for further iterations. The simple kinematics, reinforced arms and relatively simple belt and pulley system makes it a good template for the final design. The design does need some further work. The correct components must be chosen and the design must be adjusted to those components. Some weight reduction can still be done to fully optimize the model and some components of the design must be adjusted so it can be fully printed by a regular sized 3D printer. Important is also to redesign some parts to make assembly easier.

Final Design

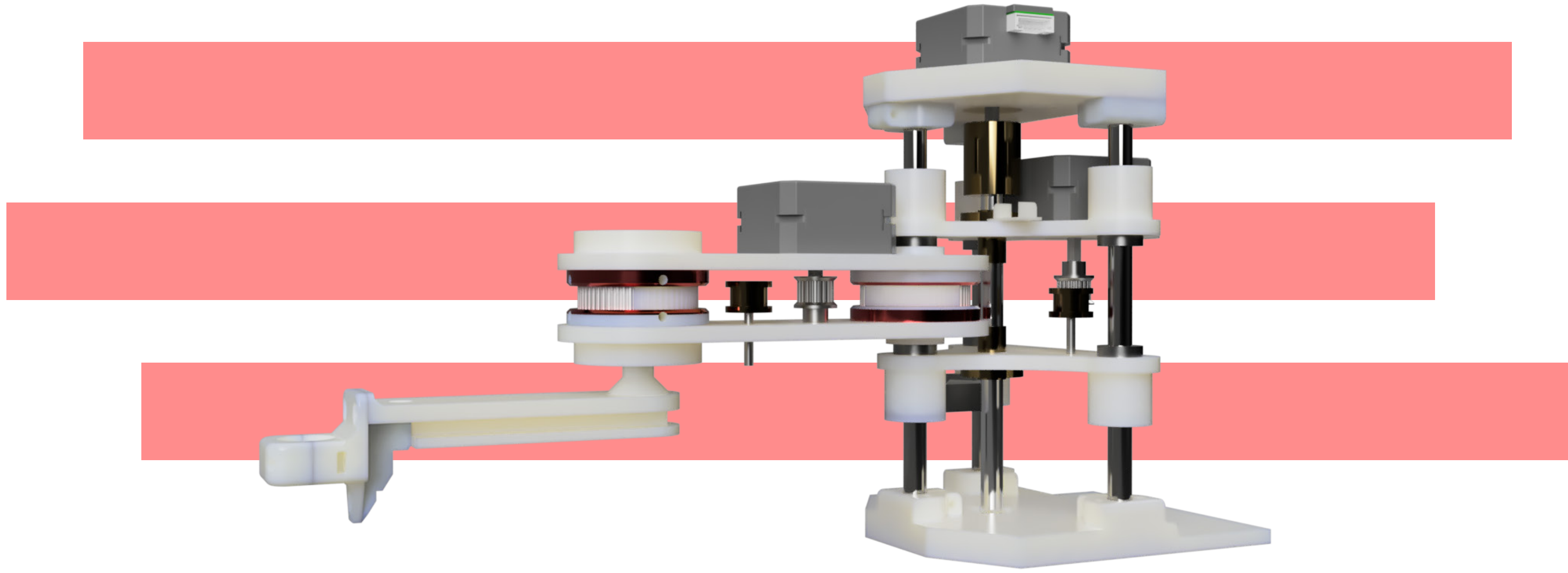


Figure 36: The final proposed design for the SCARA 3D printer mechanism.

The final design consists of 2 major assemblies; the base tower and the arm(see figure 36 & 37). In the end two custom pulleys were designed for the shoulder and elbow joints, off the shelf GT2 pulleys were causing issues with spacing. Now both of the pulleys are 60 teeth custom pulleys that provide a gear reduction ratio of 1:3. Some minor quality of life updates were added such as fasteners for the guide rods, limit switch holders and belt tensioners for an overall better assembly experience(figure 38). And the elbow arm and 'hand' has been redesigned to add strength and the ability to hold on to the E3D V6 hot-end.

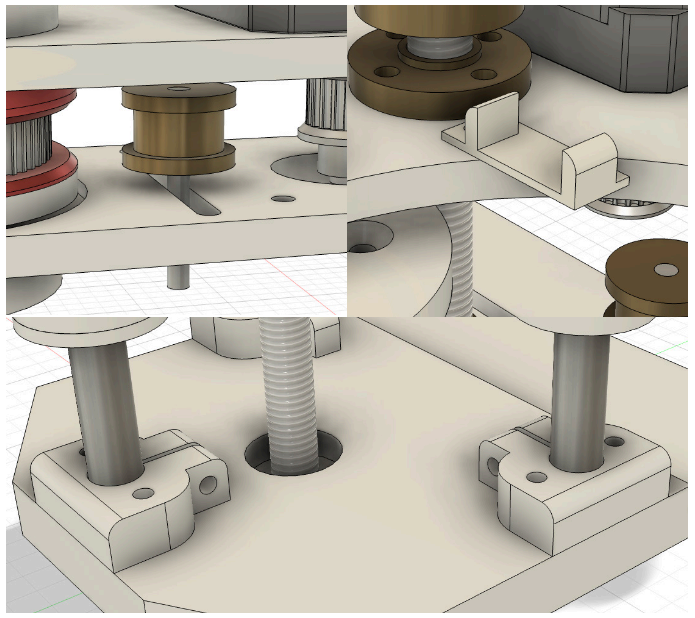


Figure 38: Quality of life improvements, tensioner pulleys (top left), limit switch holders (top right) and guide rod tensioners(bottom).

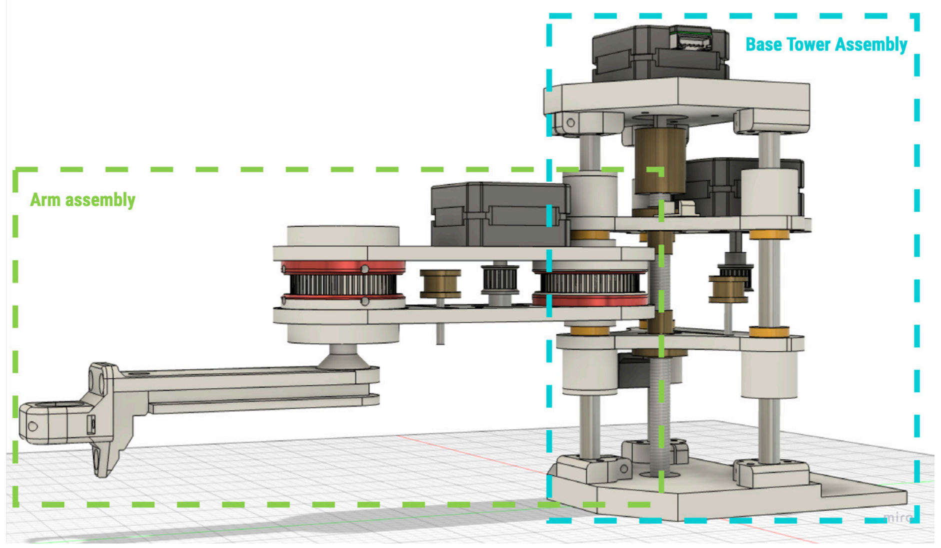


Figure 37: The final design split in its two major sections: The base tower and arm.

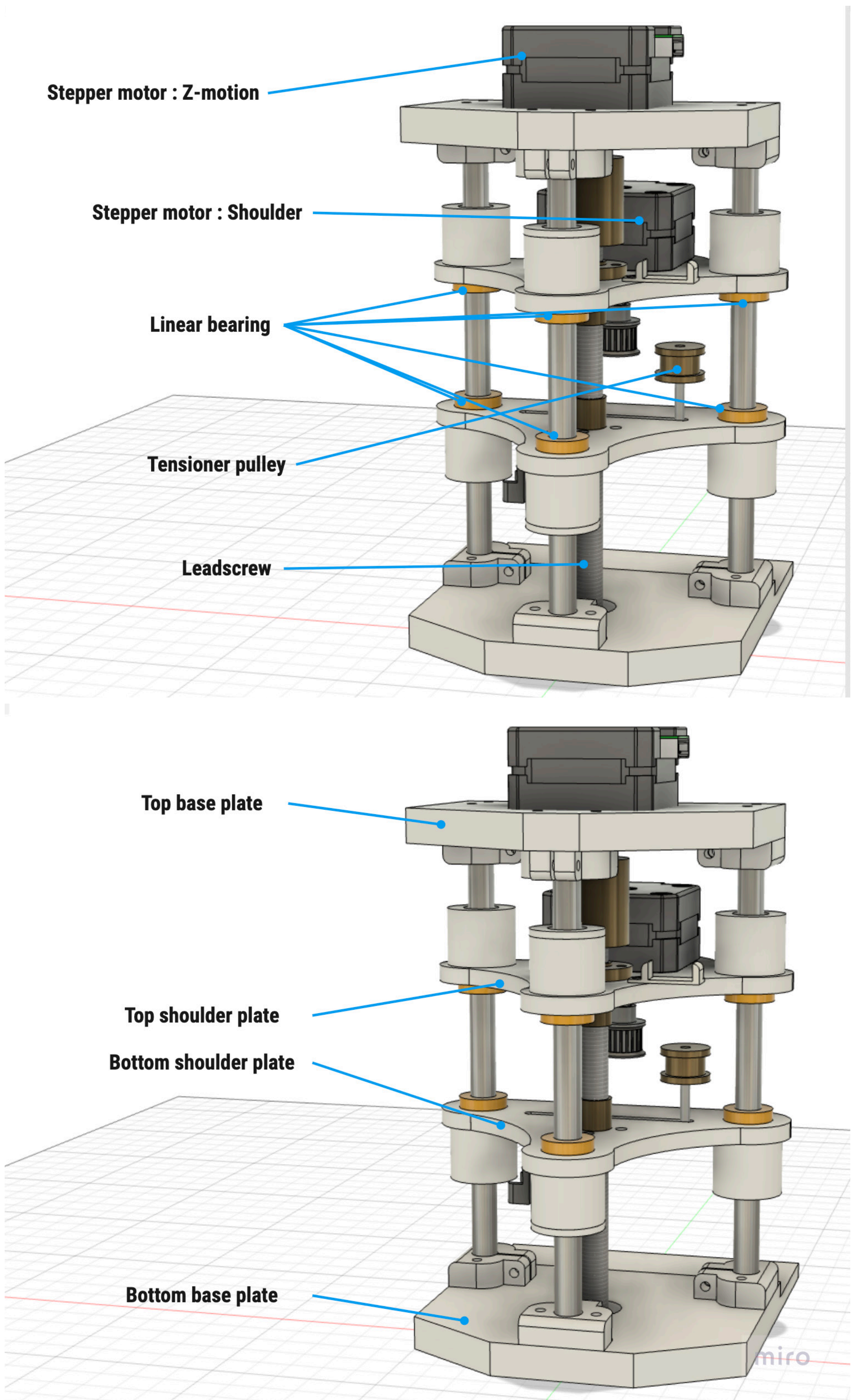


Figure 39: The Base Tower assembly and all of its components.

Base Tower

The base tower holds most of the components. The bottom base plate and top base plates are connected by the lead screw and guide rods. These base plates make sure that alignment of the lead screw through the shoulder plates is solid. The shoulder plates are connected to the guide rods by using linear bearings, therefore both plates can freely move up and down. The distance between the shoulder plates is fixed by the lead screw and arm assembly. The triangular shape of the plates in combination with the guide rods gives the base enough rigidity but also gives the option to use one of the guide rods as the rotation point for the shoulder joint. You can see the full assembly in figure 39.

Arm

The arm assembly includes the shoulder and elbow mechanism(figure 40). The shoulder pulley is fixed to the shoulder link plates by driving several nuts and bolts through the three layers. The elbow pulley on the other hand, has holes that makes it possible to insert bolts sideways in the pulley that are able to clamp down on the protrusion on top of the elbow link. To create a more robust connection and not rely on screwing into the printed material small compartments were designed into the pulley wherein a nut can be placed. The bolt will go through the holes and reach the nut, which is fixed by its shape, and therefore it can lock itself in(see figure 40a). This system is similar to off the shelf GT2 pulleys that also clamp down on stepper motor axes. The stepper motor mounting holes on the shoulder link go through both of the shoulder plates, this is done so that a 30 mm long m3 bolt can be driven through both of the plates to secure the stepper. By driving through both the plates, it reinforces the double plate design(see figure 40b).

At the shoulder end of the arm, compartments were designed to snugly fit in thrust bearings. The most front guide rod(on the base tower) is then inserted into that shoulder joint. The arm assembly will find itself in between the two shoulder plates at the base. These plates will then clamp down on the arm assembly, directly on the two thrust bearings in the shoulder joint(see figure 40c). To connect the shoulder link to the elbow link angular bearings were used. Angular bearing are so called combination bearings which means that they can endure both radial and compressive forces. Another option was to use a combination of radial and thrust bearings, but the dimensions of these would mean that the design had to be modified by a lot. The weight and size of the angular bearings are a downside though. The elbow pulley rests in between the two angular bearings, effectively creating a free rotating pulley. This gives the pulley and consequently the elbow link the ability to be driven by a stepper independently of the shoulder joint. The elbow link consists of the three components, the arm, the coupler and the hot end mount(see figure 40). The elbow link its geometry is specifically designed to reduce deflection. The first few prototypes of the model showed that most of the bending appeared in this component, it is compared to the rest of the arm the weakest link. To combat the stresses and reduce the bend an I-cross section was applied through the arm. The I-cross section was proven to be the most resistant form against deflection (see figure 41). The next critical point of the arm was found at the 90 degree bend that goes into the protrusion that connects the elbow and arm. This point was reinforced by removing the sharp corner by adding chamfers(see figure 42). The hot end mount is then simply screwed into the elbow arm and re-

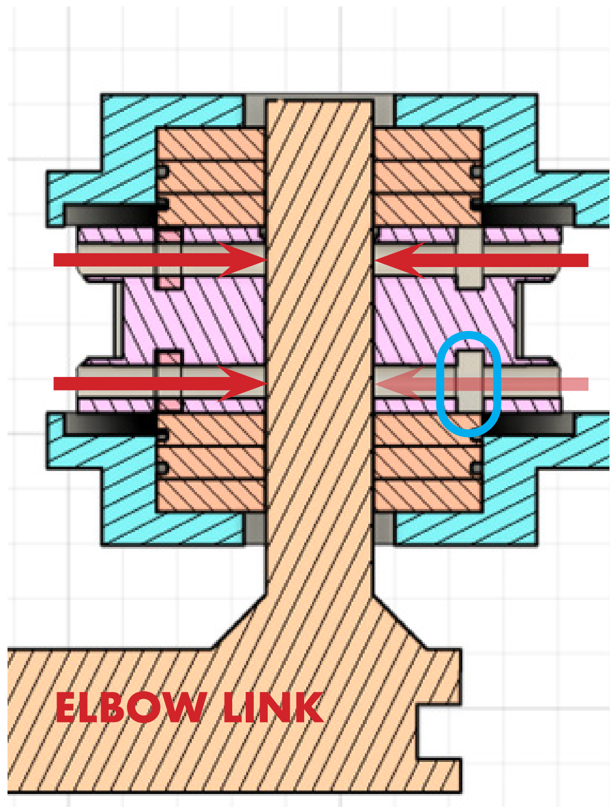


Figure 40a: Close-up of the elbow joint, the red arrows indicates where the bolts can go through. The blue circle shows one of the compartments wherein a nut can be inserted.

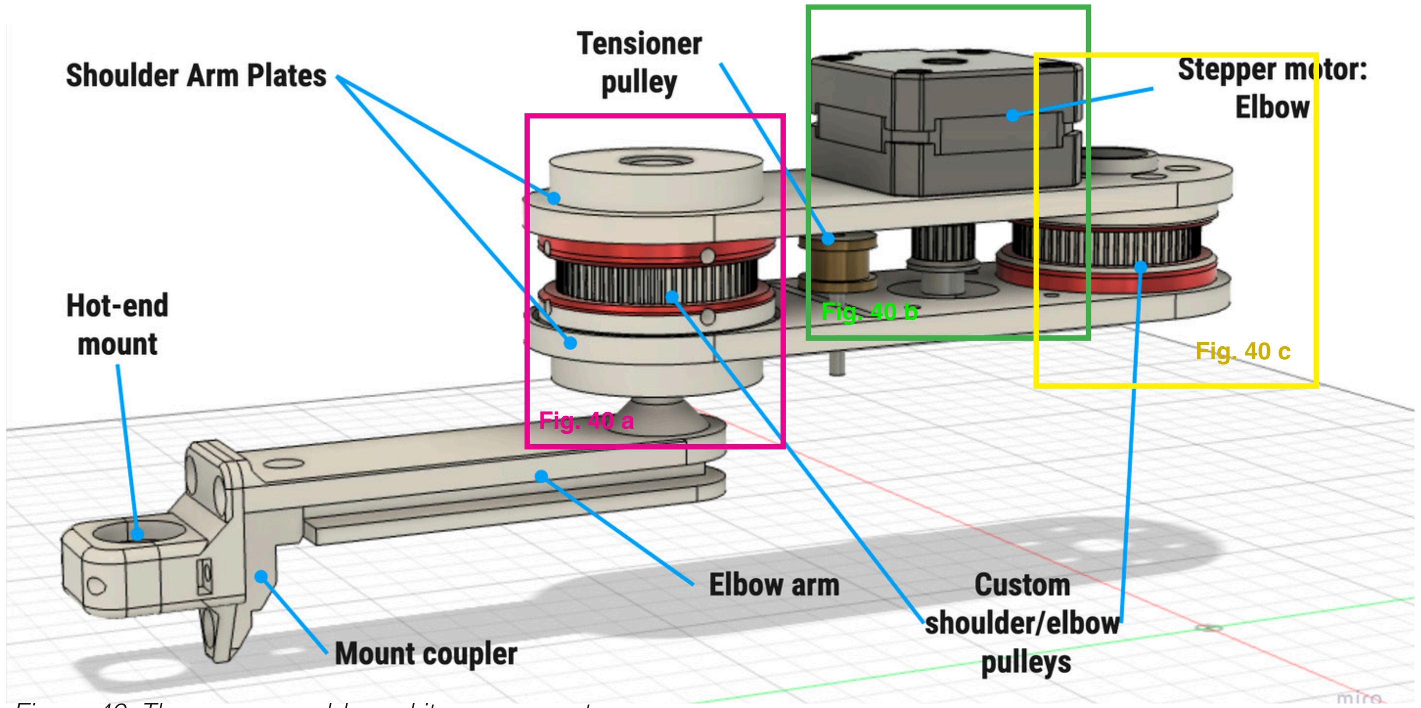


Figure 40: The arm assembly and its components.

inforced by the coupler. The radius of the mount is slightly smaller than the true radius of the hot end, this was done to be able to clamp down on the hot end using the same nuts and bolts system that was used in the elbow pulley. This was done because the mounting system originally did not have enough clamping power to prevent the hot end of spinning in its own axis when mounted.

Components

The SCARA arm is one part of the equation, to be able to properly 3D print a lot more components are necessary. All of these components are off the shelf products to simplify the design process. The main focus of the components was to keep it as simple and as light as possible. Some components that are regularly found in 3D printers were omitted as they only benefited the prints in an aesthetic manner.

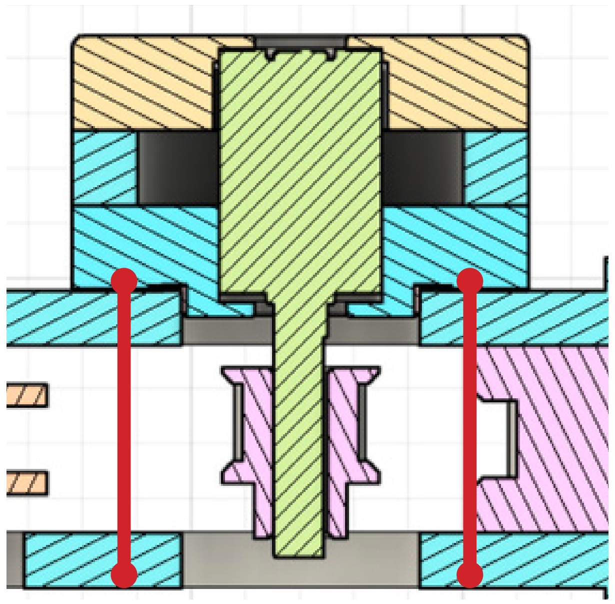


Figure 40b: Close-up of the elbow joint stepper motor, where the bolts to secure the stepper can go through both plates to reinforce the arm.

Motherboard (See table 2)

For the motherboard it was decided to use the Big Tree Tech SKR Mini E3 V3.0. This board is often used to upgrade Creality Ender 3 machines into a more silent and powerful printer. The board is rated for 12-24 Volts while implementing a 32-bit ARM Cortex-M3 processor. The BTT SKR mini E3 also has enough ports for upgrades such as BLT touch systems and extra extruders. These extra ports means it is possibile to drive extra components with the same board, so without needing extra power supply's or PCB's. The SKR E3 already comes with stepper drivers integrated into the board which makes for a compact and easy to use system. It houses the TCM2209 silent stepper drivers that are able to supply up to 2 Amps of current to the stepper motors. This makes the SKR E3 a perfect choice for a compact 3D printer with enough space to upgrade if necessary. The biggest issue in regards to the SKR E3 is the fact that it is mostly used with Ender 3's, most people do not run custom firmware on the system. Which means that specific documentation on installing custom firmware on this board is limited.

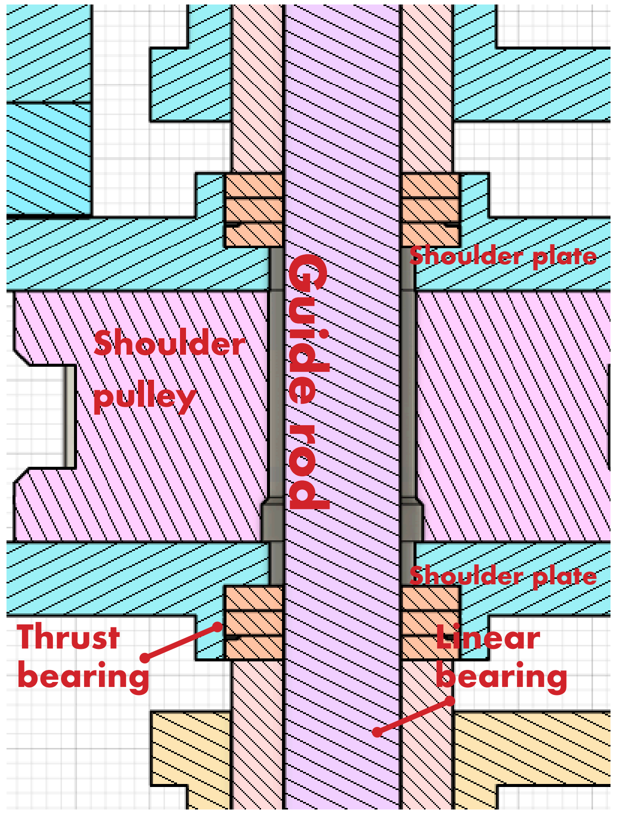


Figure 40c: Close-up of the shoulder joint and guide rod connection.

The SKR 3.0 would have been a great choice due to its focus on various machines rather than an upgrade board for a specific type of printer. The DUET boards were also considered due to their RepRap Firmware, which is known to house a fully functional SCARA build firmware. These two options were simply disregarded due to pricing and availability in the Netherlands at the time of writing.

Stepper Motors

Simple NEMA 17 stepper motors were chosen to drive the SCARA design. In regards to torque and speed, it was determined that due to the lightweight materials the required power of the steppers would be trivial. Rather the choice was based on the weight and size of steppers. This was crucial for one of the steppers, as it was placed on top of the moving shoulder link. Therefore it was decided to use NEMA 17 pancake stepper motors, they attain a holding torque of roughly ~16 N cm but weigh half as much as a regular NEMA 17 stepper. For the extruder a larger model was chosen as the size wouldn't matter as much at the base and the weight could actually help stabilize the design.

Extruders

For the extruder we opted to use one of the more basic systems that are mountable on any stepper motor given it is one of the correct size. A full metal upgrade kit for the Ender 3 models was used. The other extruders on the market performed a lot better, but came with additional weight and more complex mounting systems that took space(see Figure 43). Most of the more well known extruders were also meant to be used on direct drive systems. The aluminum MK 8 Bowden extruder does exactly what we require for a good price. Most Enders, even the more 'premium' ones use this system. Upgrading the extruder may be necessary when a more reliable system is required.

Hot end (see table 3)

Many different hot ends were considered for this design. In general, the search was for basic hot ends that were modular, so that components that weren't proven to be necessary for a good print can be removed to decrease the weight. E3D is known to produce one of the more well known hot ends, the E3d V6 All-metal Hot end. The other hot ends that were considered were good but had attributes that at this point were not necessary. For example, The Dragonfly BMS Hot end, that is capable of a larger range of temperatures and therefore was able to use more filament types. Or the E3D Revo which comes with a quick nozzle switch system. All great, but in this case only the bare minimum was required, which meant that it ended with two choices. The E3D V6 and the Lite6 which is very similar but a fraction smaller and cheaper than the regular V6. The Lite6 does reach lower tem-

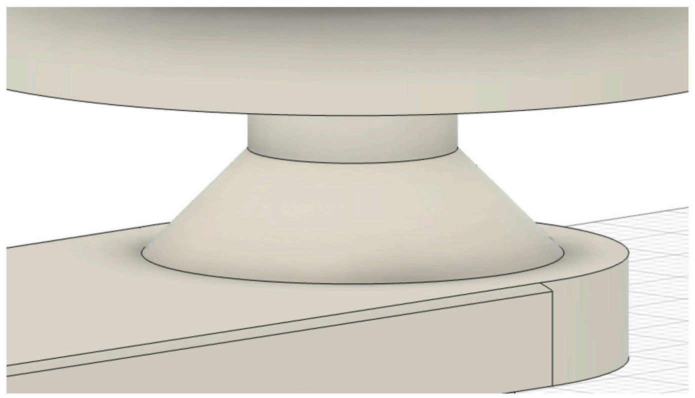


Figure 42: Close-up of the elbow joint stepper motor, where the bolts to secure the stepper can go through both plates to reinforce the arm.

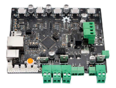
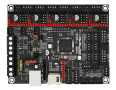
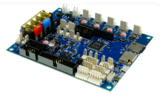
All 24 V systems	Board name	Firmware	Processing Power	Built-in drivers	Price	Extra info.
	Smoothieboard V1	Smoothieware, Marlin, Klipper	32-bit	Yes (A5984)	~€160	Uses an unique firmware called "Smoothieware", which in essence is a more polished and user friendly Marlin.
	BIG TREE TECH SKR MINI E3 V3	Marlin, Klipper	32-bit	Yes(TMC2209)	~€55	Created to be an Ender 3 replacement motherboard with silent drivers and more power. As the name suggests, a more compact variant of the SKR 3.0.
	BTT SKR 3.0	Marlin, Klipper	32-bit	No	~€90	In contrast to the SKR Mini E3 V3, the SKR3.0 is aimed for versatility. Can power all sorts of modules and extensions (like a Raspberry Pi).
	Duet 3 Mini 5+	RepRap Firmware	32-bit	Yes(TMC2209)	~€150	Most known for its proprietary firmware "RepRapFirmware" which only works on DUET boards. The firmware supports an array of movement systems, such as a SCARA system. Many extras I/O available
	RAMPS (Arduino shield)	Arduino IDE, Marlin	8-bit	No	~€20	Most basic board(or shield)

Table 2: Various 3D printer motherboards and their characteristics.

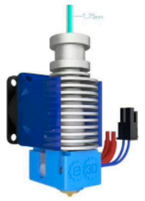
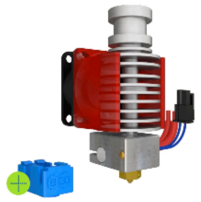
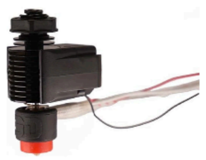
	E3D V6 All-metal Hotend	E3D Lite6 Hotend	Volcano Hotend	Dragonfly Hotend BMS	Revo Micro Hotend
					
Weight [grams]	~22 grams [E3D website]	~26 grams [E3D website]	~ 26 grams [E3D website]	~45 grams [BMS manual]	~ 30 grams [Datasheet]
Max printing temperature [°C]	285	240	285 (with sock and E3D thermistor otherwise 260)	500	300
Flowrate (PLA based tests) [mm^3/sec]	15	10	30	<20	10
Extra		Basically a simplified version of the E3D V6	Specialised hotend that focuses on flowrate, tweaking will be necessary with such hotends.	Less heatcreep, in essence a more premium V6 hotend.	Has a specialised quick switch nozzle system
Price	€70	€55	€75	€60	€150

Table 3: Various hotends and their characteristics

Figure 43: Various extruders and their price range, there are much more extruders on the market and all of them have minor to major different properties. In general though, the most simple ones should suffice.

peratures and was mainly used for PLA, which for us was is an issue. Nevertheless, the V6 was chosen because it was in the fact lighter than the "Lite6" by 22 grams when using it bare bones. Bare bones in this case meaning using the hot end without the part-cooling fan. It was considered to also not use the hot end cooling fan, but especially with cheaper hot ends heat creep can be a serious issue that causes clogging and jamming of the nozzle. The fan was purchased, but testing without will be done.

Nozzle

The nozzle is a crucial component of the printer, this component must be carefully considered as it can easily bottleneck a printer. The three main properties to consider when choosing a nozzle are the material, the diameter and the type of nozzle. The nozzle material dictates the printing temperatures achievable but it also affects the durability and lifespan. Each material has its own hardness, the more abrasive materials you work with, the higher the nozzle hardness should be. For proof of concept, the most standard brass nozzle is more than enough. It works well with PLA and while it has a relative low hardness, it won't affect the lifespan too much when only working with PLA. The type of nozzle dictates properties such as flow rate, the different types also have different distances between hot end and thermal mass which can for example help prevent secondary melting(ironing). The only interesting type of nozzle is the volcano, which can print with very high flow rates. But only changing nozzles will not add a lot of value, to achieve such high flow rates other essential components such as the hot end must be compatible. To avoid the cost, weight and complexity the industry standard MK6 nozzle was used(figure 44).The nozzle diameter has a direct effect on the flow rate (not as much effect as the volcano type) and layer height. Therefore, the larger the diameter the faster it can print. The industry standard is currently the 0.4 and 0.6 mm nozzles, this printer will ultimately look to implement the 0.8 mm nozzle. Some testing will be done with the 0.4 mm nozzle to get a baseline after which can be compared to the 0.8 mm nozzle performance. The reason not to go above a 0.8 mm nozzle for now, is that it would not work with most standard 3D printer components, same as the volcano nozzle. The types and diameter can be found in figure 44.

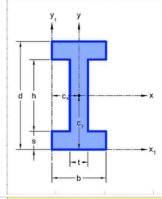
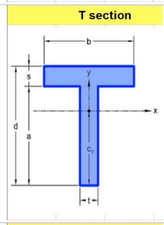
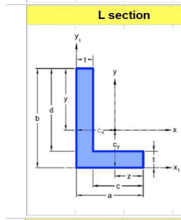
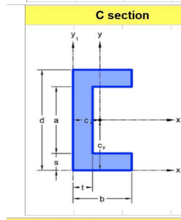
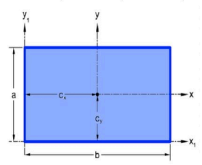
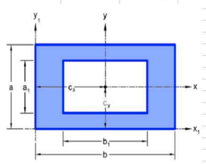
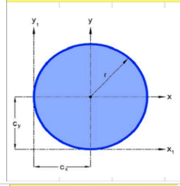
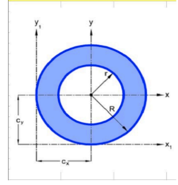
Cross-section type	σ_ max [MPa]	deflection [m]
I section 	93,217	0,001982
T section 	284,325	0,004328
L section 	80,913	0,002137
C section 	105,847	0,002250
Rectangular section 	234,375	0,006975
Hollow rectangular section 	117,188	0,002616
Circular section 	379,221	0,013696
Pipe section 	236,574	0,007041

Figure 41: Various stresses and deflections of types of cross-sections, calculated by assuming w = 500 kN/m, ρ=7800 kg/m^3, E = 210 GPa and length of the beam is 3 m. Dimensions were chosen so that the area of each beam is identical. Calculations done by Michalski (2020).

Power Supply

Important was to determine if a 12 or 24 V system was going to be implemented. In regards to safety, a 24 V system can output the same amount of power with only half the current of 12 V systems. This also means that thicker cables can be avoided for the build. 24 Volt power systems also generally increase the performance of the steppers, requires less time to heat-up and produce less noise(Florian, n.d.).So for this build it was decided to use a 24 volt power supply. To find the correct power supply it was necessary to review all the different component and their power requirements.

To accurately calculate the power consumption of a stepper motor, the rated current, voltage provided and phases must be considered. Only in this case, having a safety margin is a good thing so the simplified version of this calculation can be used that is less accurate but sufficient.

Power (watts) = Voltage x Current
Peak current (given) = 1000 mA
Voltage = 24 V

The steppers won't operate at peak current 100% of the time. To get an better estimate, it is assumed it reaches 70% peak current during operation.

Power = 24 x 1 x 0.7 = 16,8 Watts
~ 5 steppers = 84 Watts (3 steppers for printing, 2 for leveling)

The printer itself only has 3 steppers
= 50,4 Watts

E3D V6 Hot end power usage = ~ 35 Watts (E3D specsheet)

Total required power = ~85,4 Watts (only SCARA printer)

The heated bed is usually the larger power user in 3D printers, it helps alot that it can be omitted. In the end, a Meanwell 24V, 100 W power supply was chosen to be used in this setup.

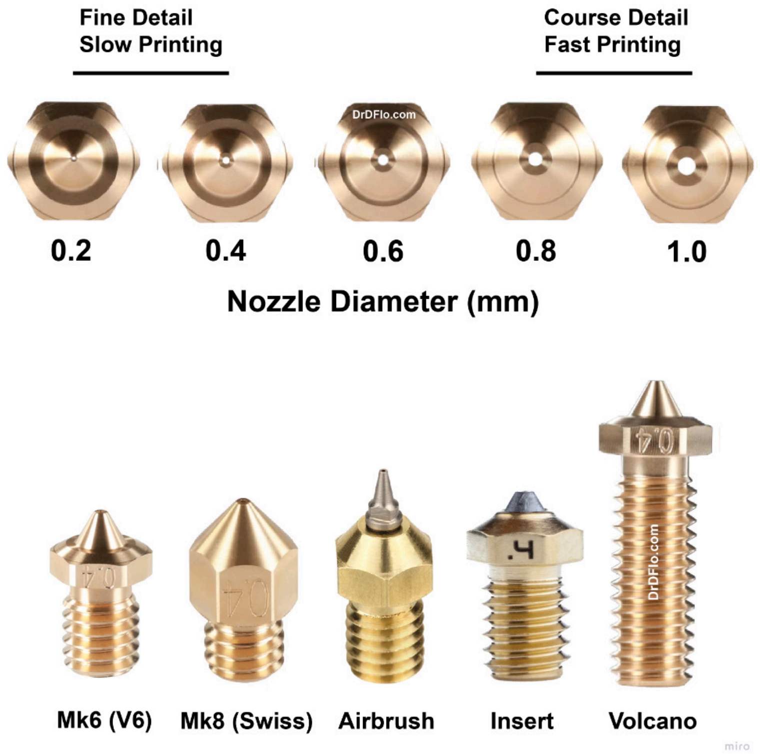


Figure 44: Various nozzle diameters and nozzle types. Adapted from D-flo(nd.)

Full proposal

For the robotic builder as a whole, the plan was to attach the printing mechanism on a mobile platform. The mobile platform must be designed with climbing and leveling as the main functions. The research has indicated that using some sorts of whegs system in combination with a rotational leveling system can be a promising solution. A conceptualization of the full builder has been designed and modeled as seen in figure 45 on the next page. This system consists of the 3 parts, the printer, the (electronic) housing and the mobile platform. The platform simple uses back driven whegs using a DC motor connection. While the back wheels are connected to a linked bar that is attached to a servo motor. This servo is able to rotate the link on which the wheg is mounted (See figure 45 bottom), creating a leveling system. The original design played around with a leveling system that moves the whole back wheel axis, but being able to move each back wheel separately will improve the leveling ability, trading off simplicity.

Due to time constraints the rest of the mobile platform was not explored to make time to design and prototype a fully functional SCARA 3D printer.

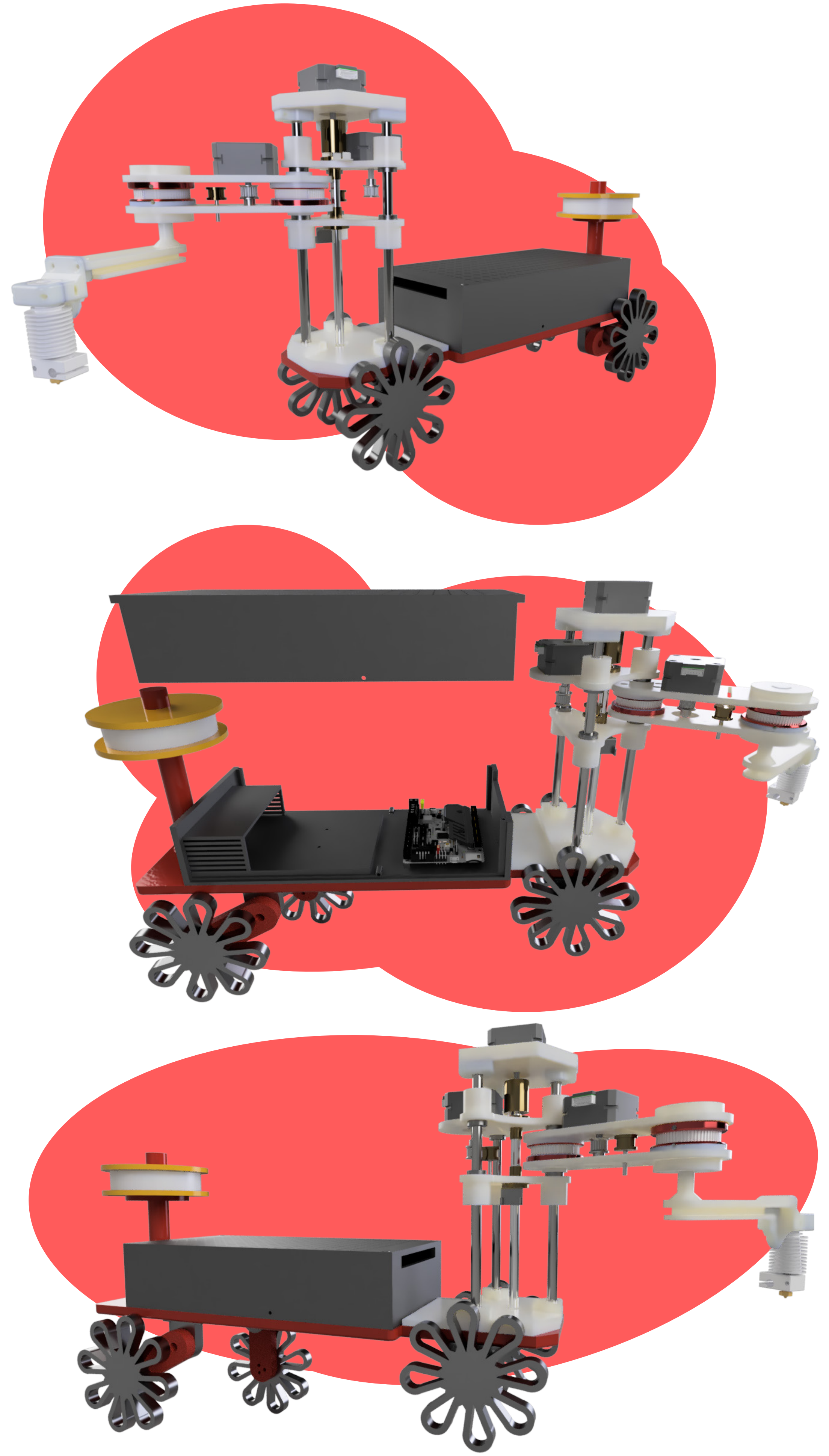


Figure 45: Fully assembled robotic builder concept, including the embodiment that houses all of the electronics, the level mechanism and wheg wheels. The builder also had the filament roll on the back. In the most bottom figure you see the leveling in action, pulling down the two back whegs, effectively push the back of the platform up.

5 Prototyping

The decision was to 3D print most of the components, including custom pulleys. The SCARA arm designs that has inspired this project, such as the X-SCARA and Arduino SCARA has shown that printed pulleys can be sufficiently effective when the belt tensioning is done properly. This allows for more opportunities to further optimize the arm section in the design. 3D printing allows rapid prototyping while still using strong materials, adding the ability to test various designs quickly.

Hardware

Printer Deviations

One of the major issues that came up early during printing of the components was the deviation that each 3D printer inherently has. Although deviations were relatively minor (0.2-0.3 mm), when combined in a mechanism, they could accumulate and lead to play. Enough play or slop can harm the accuracy, positioning and repeatability. To address this, calibration pieces were printed (see figure 46) to calculate the average deviation. This average is then used as a value for the printer's 'horizontal hole expansion' function which corrects deviations caused by thermal expansion. After implementing this function in the slicer, the backlash reduced significantly, but was not completely eliminated. Additionally, by using a calibration cube, it was observed that the printer exhibited a consistent error in the x-axis. This issue was difficult to fully resolve, but were minimized by calibration settings in the firmware.

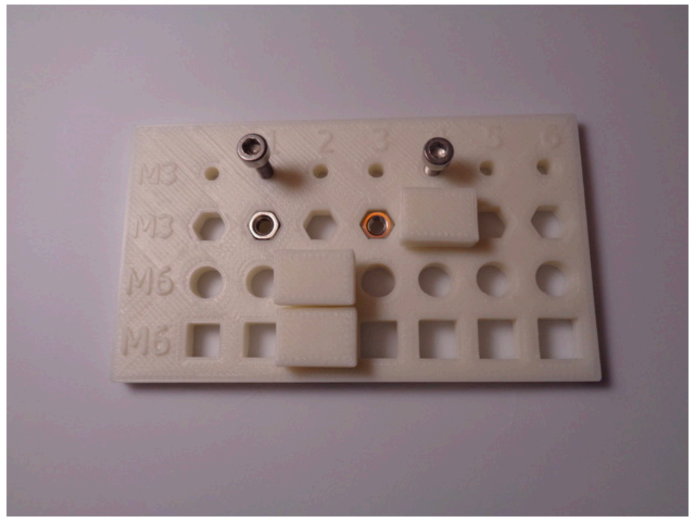


Figure 46: Hole tolerance / clearance calibration pieces.

Custom Pulleys

The custom pulleys that were designed for the elbow had one major flaw, the nuts that were designed to slide into the top and bottom face of the pulley were protruding slightly. Despite this issue being previously observed in the CAD model, it was believed to have a minimal impact. Now, the nuts are the only components touching the bearings on which the pulley rotates. Positioning the nuts to achieve a level alignment proved to be quite challenging. This caused friction and imbalances between the bearings and the elbow link, resulting in jittery movement. The pulley design also did not take into account the size of the heads of the bolts. Therefore it caused the belt to occasionally get stuck on the bolt heads, and although it never did completely halt the movement, it did cause significant vibrations. The issues were resolved by redesigning the pulleys to be taller, which allowed them to fully house the nuts and maintain enough clearance from the bolt heads. Moreover, the regular bolts were exchanged for insert bolts that had heads with a smaller circumference.(see figure 47.

Mechanical Test Run

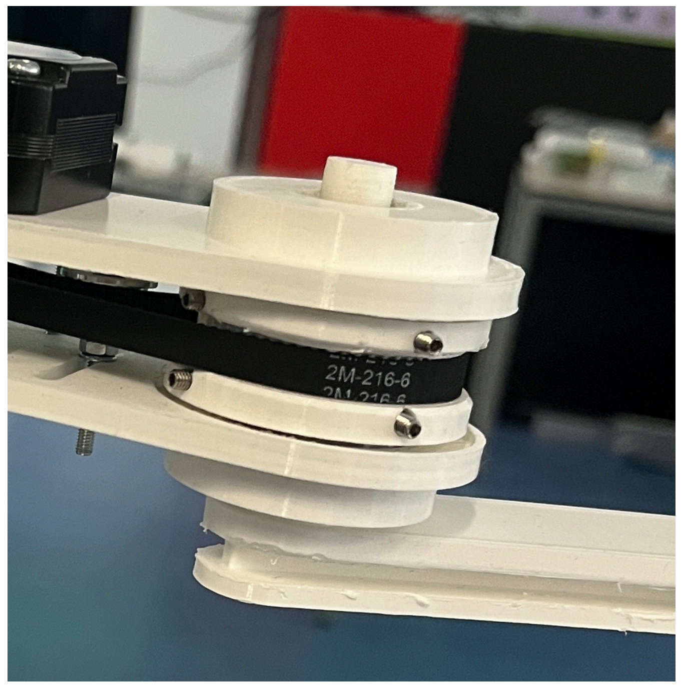


Figure 47: New pulley design including the new type of bolts.

Subsequently, a mechanical test run was conducted to assess the performance of the current components. The hot end and extruder were omitted during this test, a simple Arduino RAMPS board was used to evaluate the motion of the system. Pronterface, a software that connects your 3D printer directly to your PC, was used to give simple commands to the machine. Important to observe during the test run was:

- *XYZ movement*
- *Bearing performance*
- *Belt and pulley performance*
- *Stepper motor performance*
- *Arm rigidity*

The test run showed smooth movement in the z-axis, shoulder and elbow joint. It was also noted that the bearings performed sufficiently, but the angular bearing in the elbow joint seemed to move less smooth than the shoulder joint. This did not result in any critical problems. The shoulder houses a combination of an axial and compressive bearing, in contrast to the elbow that has angular bearings. The belt and pulley system appeared to function for both the shoulder and elbow links, but both pulleys tended to miss a step when force was applied to the links. The stepper motors were running silent and smooth but seemed to get hot to the touch after a couple of minutes of use. They didn't become much hotter after around 15 minutes of movement, though. The shoulder link and joint performed very well during the test, barely deflecting and showing no backlash. The elbow link and joint exhibited some issues; the link was easily bent due to its form factor, which removed a portion of its body to reduce weight. The connection between the shoulder link and elbow link exhibited a lot of deflection too.

The belt and pulley system appeared to be lacking tension, causing it to transfer rotation less efficiently and miss steps when force is applied. Another probable cause could be the accuracy of 3D printing, the resolution of the printed pulleys are average. To try and solve this issue, shorter belts were cut and glued together. The increased tension caused the belts to snap though. So slots were integrated into the design for tensioner pulleys (see figure 48). To strengthen the system, pre-manufactured belts were

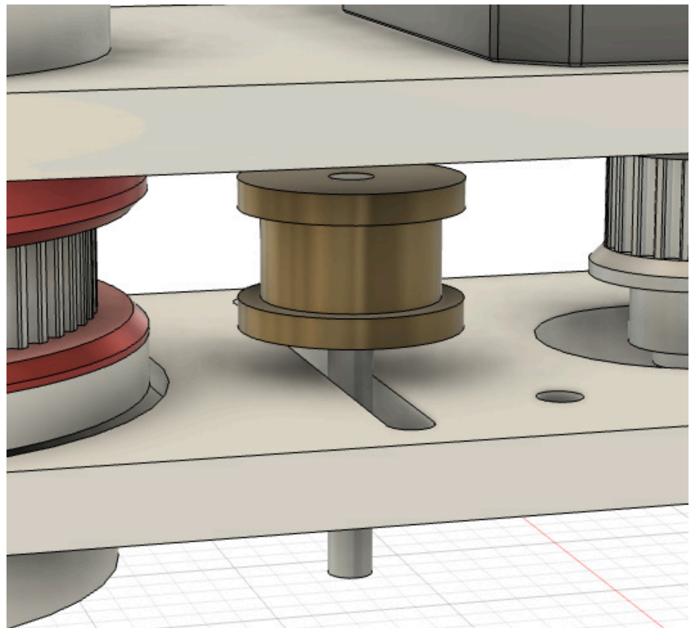


Figure 48: Slots were added later on for the tension pulleys.

used to replace the custom-sized glued belts.

The excessive heating of the stepper motors could be attributed to the relatively inexpensive stepper drivers used in the RAMPS board. The current limit was also set to the maximum rated working current of 1.0 Amperes which may have been too high, a safety factor could prevent this heating up. The temperatures should be monitored again when using the newer motherboard.

To minimize link deflection, minor changes were implemented into the embodiment of the elbow link. Chamfers were added to the cylindrical protrusion that connects the elbow and shoulder link to dissipate the stresses. Furthermore, the cross-section design of the link was changed to an I-cross section. Both of these changes focused on minimizing stresses and bend on the components.

Firmware

The open-source Marlin Firmware was chosen to operate the printer. The Marlin Firmware is known for its large community, customization options and relative ease of use. Numerous pre-configured files for all various motherboards, printers, movement systems, accessories and their combinations can be found online. For highly customized systems, such as the one used for this project, it is necessary to create and adjust configuration files tailored to the specific requirements of the setup. The already integrated SCARA code for the MP SCARA build was used as the basis for this version. The MP SCARA was another open source design that was published in 2017 by "Williaty" (Williaty, 2017). The X-SCARA code was originally used as the foundation, but the firmware has issues syncing with newer versions of Marlin. Some basic modifications to the configuration files that were added are the following:

- *MCU(Micro controller) settings*
- *Motherboard*
- *Driver type*
- *Hot end sensor*
- *Enabling the basic SCARA functions*
- *SCARA parameters*
- *The steps per unit*
- *Bed size dimensions*
- *Enabling EEPROM setting*

These changes were all done in the standard configuration file of Marlin (configuration.h). Simple definition lines were added, enabled or disabled.

The next step involved defining the physical setup of the printer. In this case, the SCARA-mode had to be enabled which essentially does IK(inverse kinematics) to get the angle coordinates for the arm segments. For the IK to be effective, the setup needs to be mapped in the firmware by defining offsets and bed dimensions, and then integrating those parameters into the calculations. An overhead view of the setup and its dimensions can be found in figure 49.

With the overview, the offsets can be defined to get a proper IK and FK(forward kinematics) model. The shoulder offsets relative to the print bed origin can be easily input into the configuration files. Same for the bed dimensions, given it falls within the physical limitations of the SCARA arm model. The link lengths must be measured from endpoint to endpoint. SCARA segments per seconds is the variable that decides how many discrete steps are taken to follow a complex path. The firmware breaks down the continuous motion in smaller straight line segments for the SCARA to follow near the actual path. The more (and shorter) lines there are, the smoother the motion, which also means more computational overhead. The 32-bit micro-controller gives the design more performance. With a 8-bit MCU this value should probably go down to 50-100, while this model can go up to 200.

Additionally, some minor details of the build

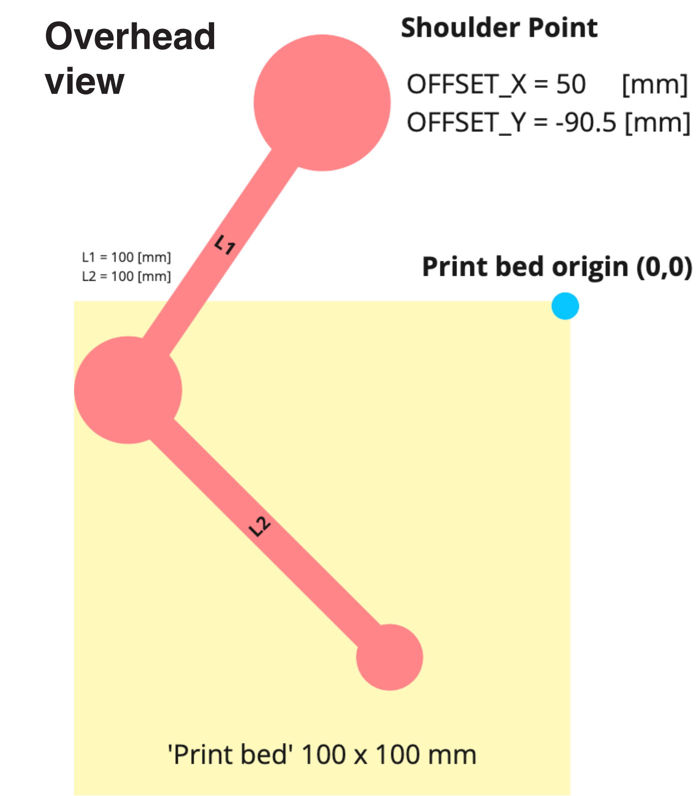


Figure 49: Overhead schematic of the SCARA arm setup and its parameters.

needs to configured. The step size per unit needs to be calculated, this number is the amount of steps necessary to rotate 1 degree. This calculation is specific to SCARA machines, and generally, the rule involves determining the steps required for 1 millimeter of travel. This calculation includes the stepper resolution, micro stepping and the gear reduction ratio. With the given 1.8 degree resolution, 1/16 micro stepping and gear reduction ratio of 3:1, the steps per rotation for the shoulder and elbow steppers can be calculated by the following equation:

*Step size per unit = ((360/1.8) * 16 * 3) /360 = 26.67 [steps per degree of rotation]*

Enabling the EEPROM configuration means printer settings can be modified and saved in real-time using G-CODE commands.

Inverse Kinematics

Relative simple trigonometry was used for the inverse kinematics in the firmware. You can see most of the code in figure 50. Three angles are defined. THETA1 is the angle between L1 and the x-axis, THETA2 is the angle between L2 and the x-axis and THETA3 is the angle between the x-axis and the line going from shoulder joint towards the end effector (see figure 51). For THETA1 and THETA2 the law of cosines is used on

```
void inverse_kinematics(const xyz_pos_t &raw) {
// Theta3 is angle from shoulder to nozzle. c is distance from shoulder to nozzle.
// The shoulder-to-nozzle line, proximal arm, and distal arm make up a triangle,
// so the "law of cosines" can be used to calculate the shoulder and elbow angles.
const float x = raw.x - scara_offset.x, y = raw.y - scara_offset.y,
            hand = SCARA_IS_RIGHT_HANDED ? 1 : -1,
            THETA3 = ATAN2(y, x), c2 = HYPOT2(x, y), rc = RSQRT(c2),
            THETA1 = THETA3 - hand * ACOS((c2 + sq(L1) - sq(L2)) * rc * RECIPROCAL(2.0f * L1)),
            THETA2 = THETA3 + hand * ACOS((c2 + sq(L2) - sq(L1)) * rc * RECIPROCAL(2.0f * L2));
```

Figure 50: The code for the inverse kinematics calculation, found in the scara.cpp file in the Marlin directory.

the triangle formed by S, E and ee. Important to note is that offsets of the shoulder are also used in this calculation. To be able to work in a right handed or left handed system one more variable was added. The SCARA_IS_RIGHT_HANDED value can be input in the main configuration file, by adjusting that value to 1 or 0 the system can work in both RHS and LHS.

General testing & iterations

Kinematics

To test the newly installed firmware, the same third party software was used that is able to connect the printer directly to a computer. "Pron-

```
delta.set(DEGREES(THETA1), DEGREES(THETA2 - THETA1 * SCARA_CROSSTALK_FACTOR), raw.z);
```

Figure 50b: SCARA_CROSSTALK_FACTOR variable that adds options for intermediate pulley systems.

terface" also has a serial input system directly for G-CODE commands. Initial tests revealed some kind of an error in the firmware code. While the elbow and shoulder stepper were turning simultaneously when moving in the X and Y direction, it was not able to produce a straight line. When mapping out the corners of the bed, instead of a square bed, it mapped out a skewed rectangle(see figure 52). It was able to repeat this skewed rectangle numerous times without issues. All of this indicated an error in the inverse kinematics, rather than a mechanical error like slipping. Upon closer examination, it appeared that the original MP SCARA code and build utilized an intermediate pulley system. Meaning that the angle between link L2 and the x-axis stayed consistent when the shoulder rotated. In this design, the angle between L1 and L2 stays consistent when the shoulder is turning. So, a variable was added for the code to be able to work with non-intermediate pulley systems. The SCARA_CROSSTALK_FACTOR will adjust the coordinates for the elbow stepper by deducting the THETA1 angle from its calculated THETA2. If an intermediate pulley is used, the crosstalk factor can be set to zero(figure 50b). With this final adjustment, the kinematics of the system were working smoothly.

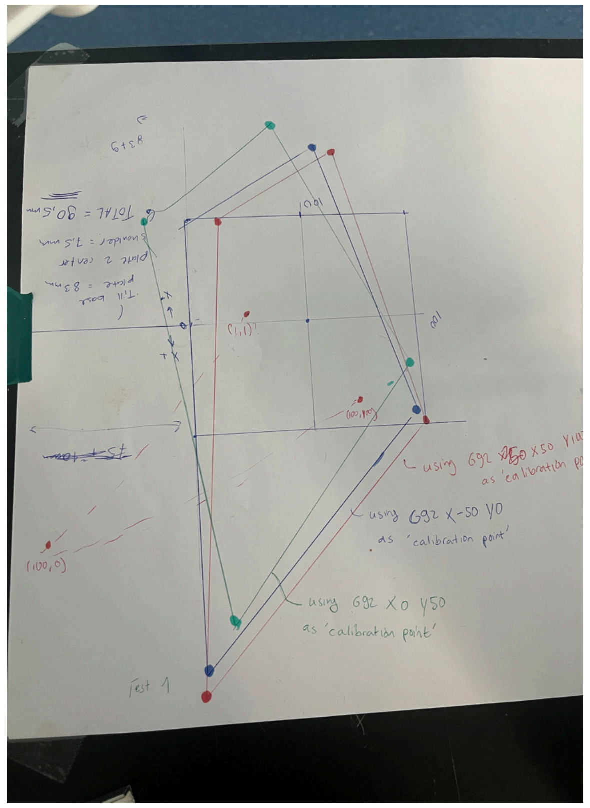


Figure 52: At first, the SCARA was not able to produce the square bed space, but a skewed variant of it.

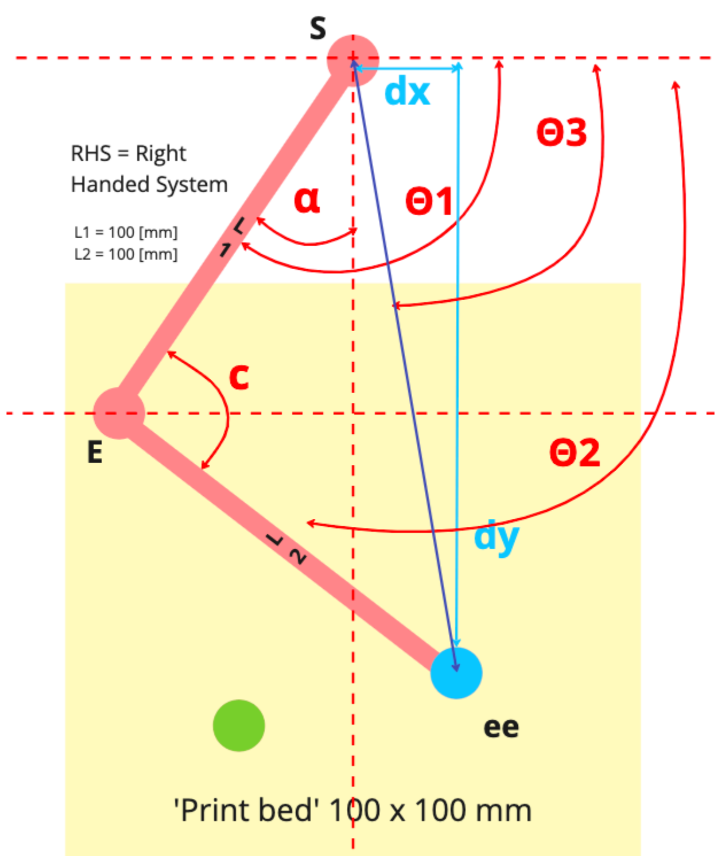


Figure 51: Overhead view of the SCARA setup and the variables used in the IK calculations.

Heating limits

The following step involved conducting a dry run of the printing process to assess how the printer performs over extended durations. The start of the test looked promising, the kinematics work well and the belt and pulley system held up. All the other components operated as they should. At the halfway point of the print (approximately 30 minutes), the stepper motors appeared to be running excessively hot. At the 60% mark the steppers in the shoulder and elbow reached 75 °C, while their rated working temperature is 80 °C. At around the 75% mark the steppers were reaching 80+°C and the test run was halted to prevent damaging the steppers and its drivers. Another curious insight gained during the testing, was that the hot end ended up being loose after the first dry print test. Although the nuts and bolts were able to be re-tightened, that does not necessarily indicate that they unscrewed themselves during the print. The design of the mount system allows the nuts and bolts to be able to be tightened indefinitely, meaning there is a possibility something else was the reason. Further testing was necessary to inspect the heating up of the steppers and hot end wobble.

The system did a dry run of the same "Benchy" model using the same slicer settings. At intervals the hottest detected temperature of each stepper and hot end was measured using a IR gun in combination with IR photos. At 80 °C, the print will be stopped to prevent damaging the steppers. The hot end mount will also observed during these intervals and tested for its rigidity. The results of this test run be found in table 4. Good to note is that the temperature of the extruder stepper motor was not measured, by 'dry printing' there was essentially no load for the stepper allowing it to run at very low temperatures.

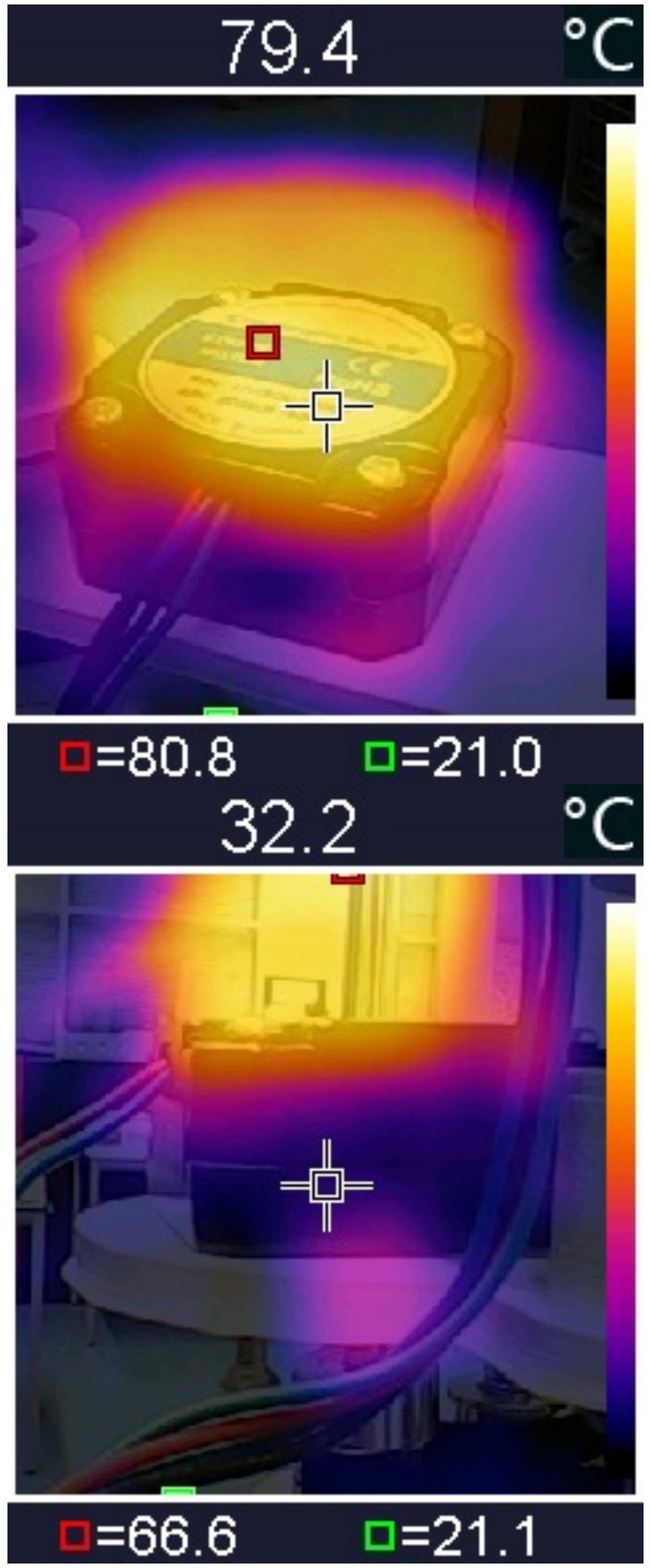


Figure 53: IR photos taken at intervals during the dry run test, heat seems to collect at the top and temperatures reach critical points before the print is finished.

The stepper's their temperatures increased significantly during printing, reaching its maximum operating temperature at around 40 minutes (75% of the print). At this point the print was stopped. The incremental increase in temperature indicates that the steppers are probably functioning normally, but may not be handling the load well. At the 75% interval it was

Percentage print (Benchy) | Total est. print time: 58 mins	T S stepper [°C]	T E stepper [°C]	T Z stepper [°C]	T Hotend [°C]
12.5 %	49	48	25	141.4
25%	62.8	58.9	36	153.1
50%	75.5	74	42	142
75%	81.6	80.8	44.6	141

Table 4: Temperature measurements of the dry run, running at 950 mA with no hot end cooling fan.

also found that the hot end started wobbling in mount again. By observation, it was concluded that the nuts and bolts did not unscrew themselves. One good thing that came out of the test was that most of the heat seemed to collect above the steppers, not on the bottom where it rests on the plastic filament(see figure 53).

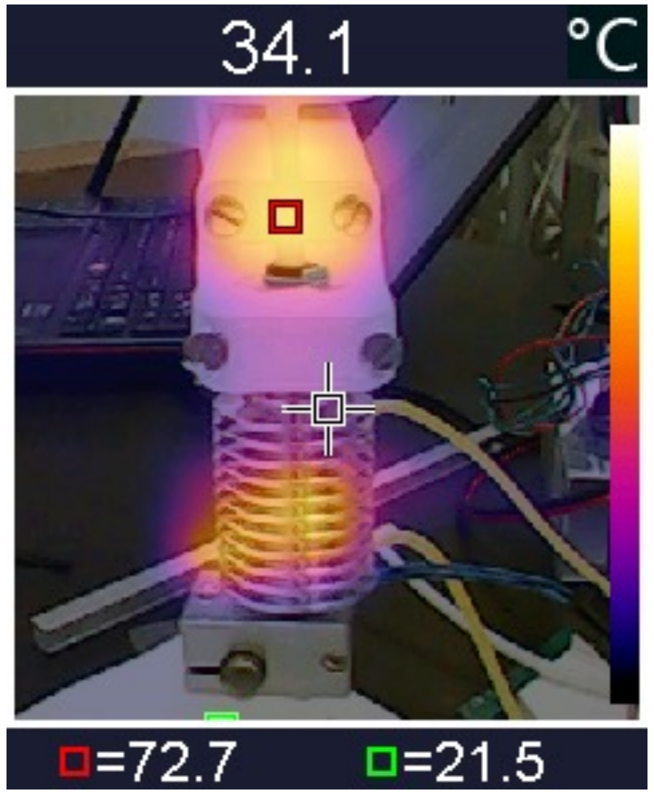


Figure 54: IR photo taken of the hot end mount during the dry run test, the heat creep reaches the cold end part and the mounting system.

Since the stepper motors appear to be functioning normally, the cause for them reaching their maximum temperatures so quickly could be related to the current limit settings on the motherboard. The steppers are rated for 1000 mA current, the system limits the current at 950 mA, which may be too close to its peak current. The hot end wobble may be caused by the hot end heating up the mount too much. Looking at the heat photos that were taken, it looks like significant heat creep is happening between the hot end and cold end. The heat reaches the point where the hot end and the mount connect, reaching temperatures of 70°C (see figure 54). This might be the reason for why the hot end starts wobbling during printing, PLA starts being pliable at 60°C.

Percentage print (Benchy)|Total est. print time: 58 mins	T S stepper [°C]	T E stepper [°C]	T Z stepper [°C]	T Hotend [°C]
12.5 %	41	40	33.3	142
25%	50	49	35	141
50%	58.5	58.1	43	140.5
75% (MAXED OUT)	63	62.2	46.6	141

Table 5: Temperature measurement of the second dry run test running at 800 mA with the cooling fan attached.

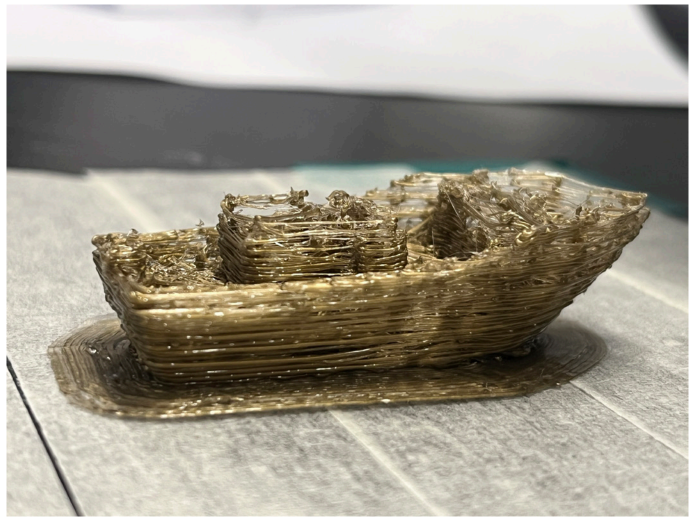


Figure XXX: First attempt of printing the well known "Benchy" model.

For the next dry run test, the current will be limited at 800 mA with the goal of having a more stable temperature output. To battle the heat creep in the hot end, the cooling fan accessory is attached to the hot end. The original idea was to omit the fan to keep the arm as lightweight as possible. After these 2 modifications, the test was done exactly the same way as the previous time. The results for the second run can be found in table 5.

The results of this dry run indicates that the system is stable now. The temperatures of the steppers in general were lower and seem to rise with a slower rate. At 75% mark, the temperatures also maxed out at around 63 degrees. The final temperature upon reaching the 100% point were 64, 63 and 47 degrees for the elbow, shoulder and Z stepper motors respectively. The hot end remained securely attached onto its mount for the whole print, meaning that the heat creep was the issue, but luckily it is easily avoidable by using the cooling fan. The increased weight of the arm has not caused any issues during the test.

Printing

The final step was to run the very first full print. All of the components were setup and calibrated first. Currently, the build has no homing sensors setup, so 'homing' is done manually by positioning the links into a specific position and using G-CODE commands to tell the system how its currently orientated. With that information, the firmware can calculate the angles of the links and update its own location. In this case, the easiest method was to get the links as straight as possible (where both arms are fully 'stretched out'), with the G92 command the user can tell the printer its current X and Y coordinates which the firmware then uses to do IK to get the THETA1 and THETA2 angles. The X and Y coordinates for the arms fully stretched out can be simply calculated with the origin map, SCARA shoulder offsets and the lengths of the links. In this orientation, THETA1 and THETA2 must be 90 degrees. This method works great for quick testing, but is obviously not as accurate as utilizing homing sensors.

The results of the first attempt at printing a "Benchy" model can be seen in figure 55. The printed component highlighted a major under extrusion issue. In the figure it is very obvious that due to the under extrusion, proper adhesion was hard to reach. The under extrusion got so bad at the later layers, that it completely stopped extruding causing the print to end up like in figure 55. Also, a clicking sound was coming from the extruder during the print, upon further inspection it looked like the extruder was skipping steps. It looked like the stepper did not have enough torque to pull on the filament. The rated current of the stepper is 1200 mA, the limit was increased to 1100 mA with no notable effects. The stepper used for extrusion was a pancake stepper, which has 16 Ncm torque. This is 2-3 times less torque than a regular stepper. Part of the problem could also have been the hot end creep, causing clogging issues. A needle was used to clear out potential debris in the nozzle, under extrusion remained the same. The kinematics of the system appear to perform adequately, with the lines being accurately placed at the proper points and demonstrating repeatability.

Increasing the rate
The pancake stepper was then exchanged for a regular stepper which seem to solve the clicking sound and therefore supposedly the skipping of steps. The pancake steppers as previously mentioned, were chosen to keep the weight on the links as minimal as possible. Due to the extruder not being placed on the arms but on the base, having a heavier stepper motor for the extruder can even be beneficial for increased balance of the system. Another modification that was

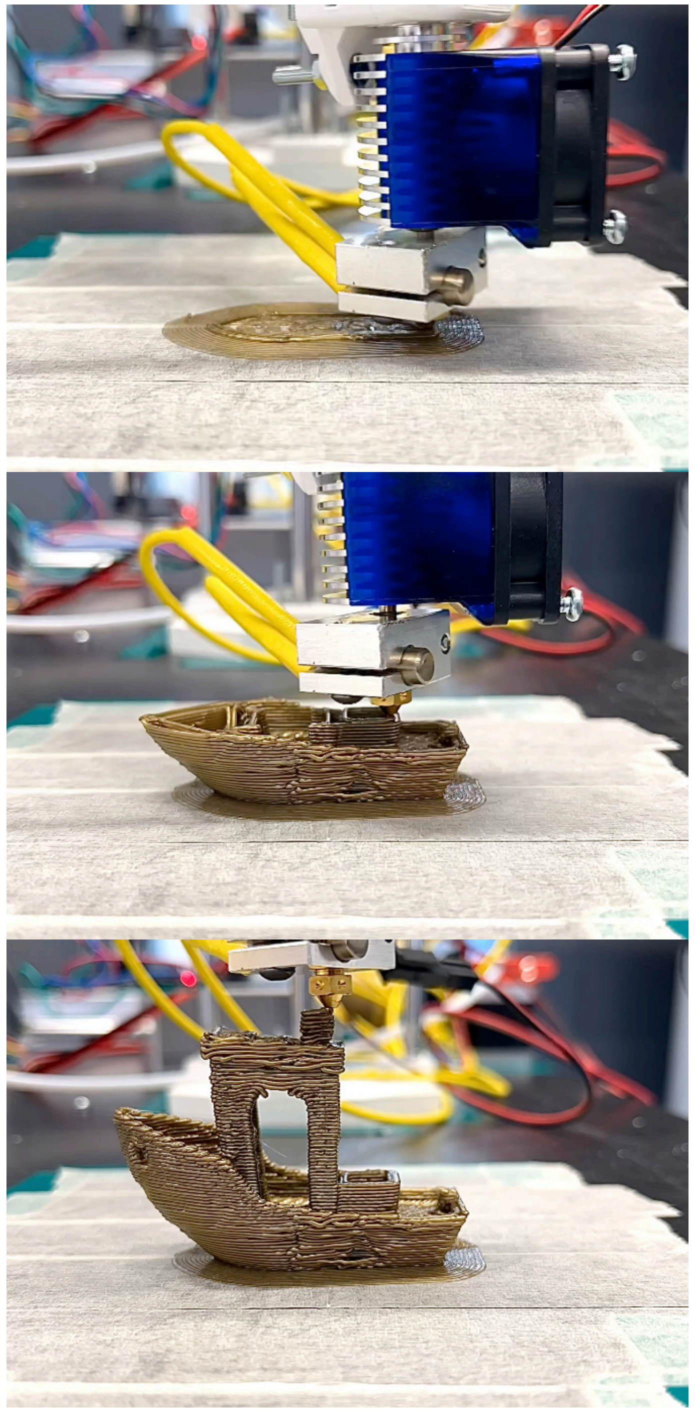


Figure 56: Screenshots of the timelapse taken of printing the Benchy model, using the regular stepper motor for extrusion and the 0.8 mm nozzle for the first time.

done was switching out the 0.4 mm nozzle with a 0.8 mm nozzle. The train of thought was that for the context of the builder, having the precision of 0.4 mm nozzle was not necessary and that the increased rate of flow may also improve the under extrusion issue and prevent clogging.

The results of printing with the new extruder stepper motor and a 0.8 mm nozzle can be seen in the screenshots of the timelapse in figure 56. The modifications helped in decreasing print time and avoid under extrusion. This print took a total of 40 minutes, while it took the 0.4 mm nozzle setup 58 minutes for the print to finish. Minor sagging happened at the top, which is possibly caused by the thicker heavier lines thar are used and lack off part cooling fan. But all in all, a quite succesful print with a good enough resolution and durability. With these adjustments, the SCARA arm printer was now fully functional and ready for further testing using the voxel structures.

6 Results

In this chapter, the results from the various tests performed with the SCARA 3D printer prototype are presented. A total of nine voxel print tests were conducted to evaluate the printer's performance in terms of print quality, speed, and accuracy. Afterwards, some testing was done in regards to evaluating the stacking capability of the printer.

Optimizing Voxel Printing

The voxel print tests were performed using the same CAD model, a large rectangle with dimensions of 160 x 40 x 30 mm. The goal was to find the optimal settings for the printer while maintaining structural integrity and efficiency. In the context of robotic builders, the main focus will be optimize the speed while maintaining integrity. Resolution and precision are important but not the main goals.

Throughout the series of tests, several adjustments were made to the printer settings to optimize its performance. These adjustments aimed to address observed issues such as random accelerations, under-extrusion, layer misalignment, and overall print quality. The main adjustments made between the tests included changes in print speed, infill pattern, temperature, extruder current limit, SCARA segment calculation rate, jerk acceleration, and flowrate. During each print, observations are done and the print time and accuracy are measured. Accuracy is measured by comparing the printed dimensions with the supposed dimensions. Of each dimension a percentage is calculated by dividing the delta to the supposed dimension. For each axis, three measurement points are taken and averaged (See appendix A for full calculation sheet). The best voxel is also evaluated for compressive forces by a stress strain machine, it will be compared to a voxel printed by a regular 3D printer. The results of each test are in figure 57 here below:

Voxel Print Test 1

- Print time: 40 minutes
- Occasional under-extrusion at two segments along the longest sides of the rectangle (see figure 58)
- Accurate X and Y movement
- Good layer adhesion, with visible lines due to the large layer height
- Some sagging on the roof of the structure
- The structure showed enough compressive strength

Voxel Print Test 2

Adjustments: Print speed to 40 mm/s(previously 60), infill 10% (Cubic Subdivision pattern), and hot end temperature raised to 240 degrees Celsius.

The goals of these adjustments were to improve the sagging, layer adhesion and avoid random accelerations. The cubic subdivision pattern creates more infill patterns which in theory should prevent the sagging by creating

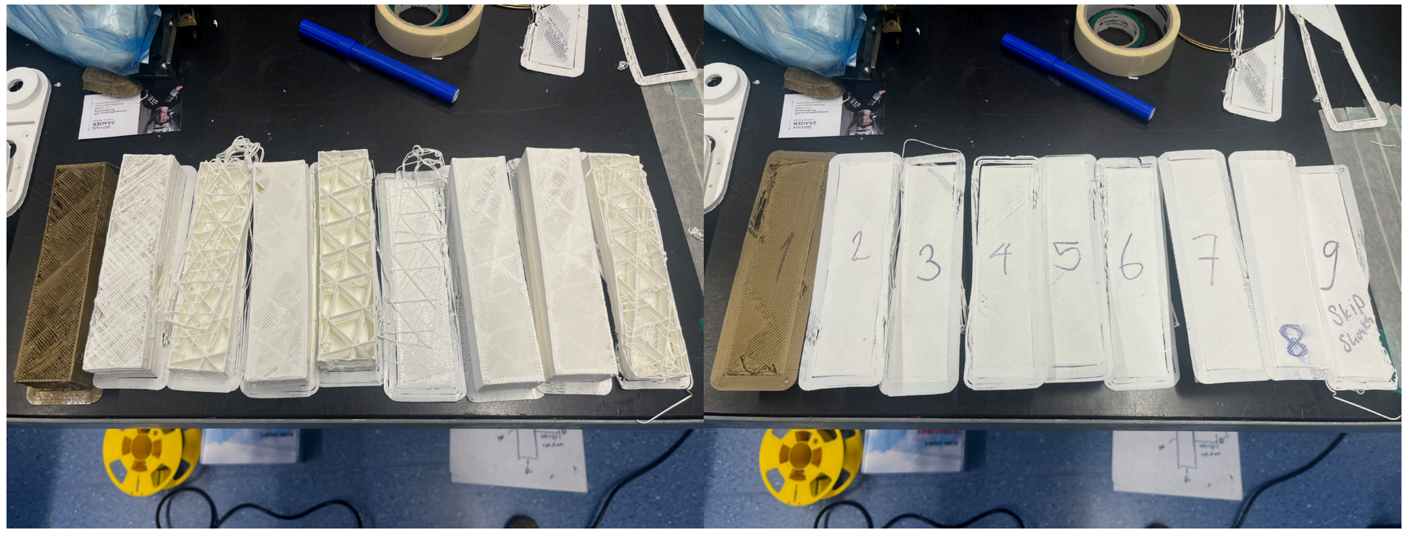


Figure 57: Testprint results of the proposed voxel, starting from the left(first print) and ending to right (last print).

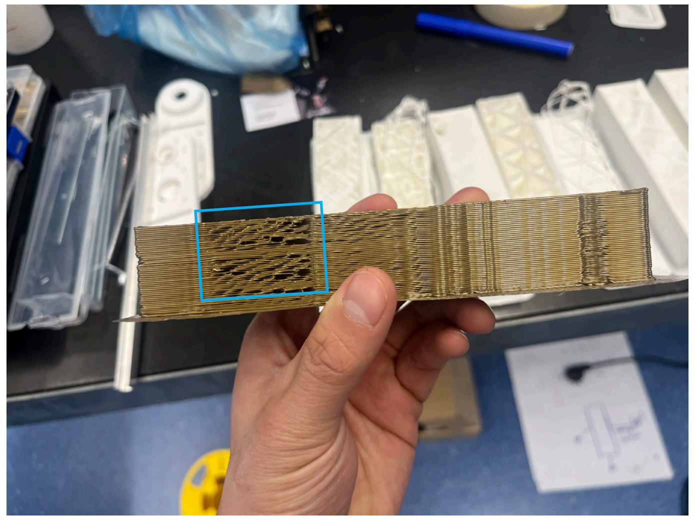


Figure 58: Voxel printed during the first test, at the long side of the voxels acceleration segments causes under extrusion.

enough surfaces for the top layer to rest on.

- Print time: 59 minutes
- Acceleration issues at the same segments as the previous test
- Significant under-extrusion issues at those accelerated segments (see figure 59)
- Poor infill, nozzle found it hard to follow the complex infill pattern path

Voxel Print Test 3

Adjustments: Infill 10% (Triangles pattern), extruder current limit set to 1.5 Ampere, and print speed to 35 mm/s.

Under extrusion seemed to get worse, to improve this, the extruder was allowed more current and therefore torque, print speed was reduced and the triangles pattern was selected to avoid complex calculations. As it could have been the calculations that were slowing done the MCU and therefore the extruder.

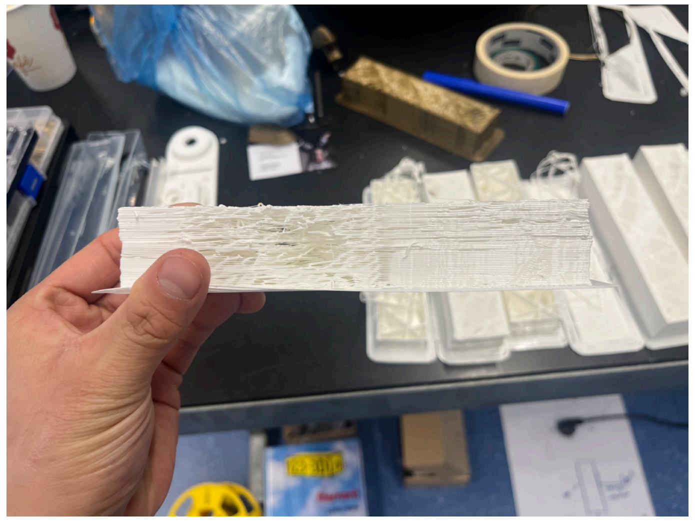


Figure 59: Voxel printed during the second test, the under extrusion and adhesion problems seem to get worse.

- Print failed after 48 minutes
- It looks like a layer was shifted diagonally, it was still able to replicate the outline of the shape but placed it wrong (see figure 60)
- Could be the shoulder pulley skipping steps somehow
- Acceleration issues persisted at the same segments

Voxel Print Test 4

Adjustments: Same as test 3, but SCARA_SEGMENTS_PER_SECOND set to 100 and jerk acceleration settings for X and Y reduced to 3 [mm/s].

Although the previous print failed, the acceleration segments were still observed during the first few layers of the print. Therefore the scara segments per second and jerk acceleration settings were reduced to try and avoid this.

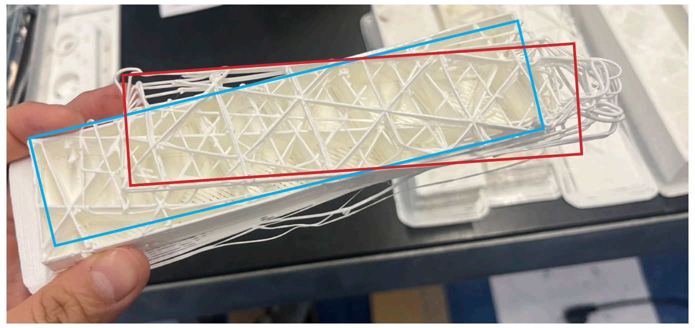


Figure 60: The third failed print of the voxel, it seems to have started misaligning the layer mid-print.

- Print time: 1 hour and 15 minutes
- Less aggressive acceleration at the same segments
- A lot of misaligning of the layers started happening, creating a 'wave' type structure in the z-direction(See figure 61)
- Less under-extrusion issues
- Improved roof layer, better adhesion and less sagging
- Strongest structure in terms of compressive force resistance up until now

Voxel Print Test 5

Adjustments: SCARA_SEGMENTS_PER_SECOND set to 150.

The wave pattern in the z-direction is a new issue, it is not critical but could definitely be a larger problem over longer prints. One of the newer adjustments must be the reason for this effect. If increasing the segments per second slowly to 200 works, that means that the jerk is related to the acceleration issues and the segments per second is causing the misalignment(see figure 62).

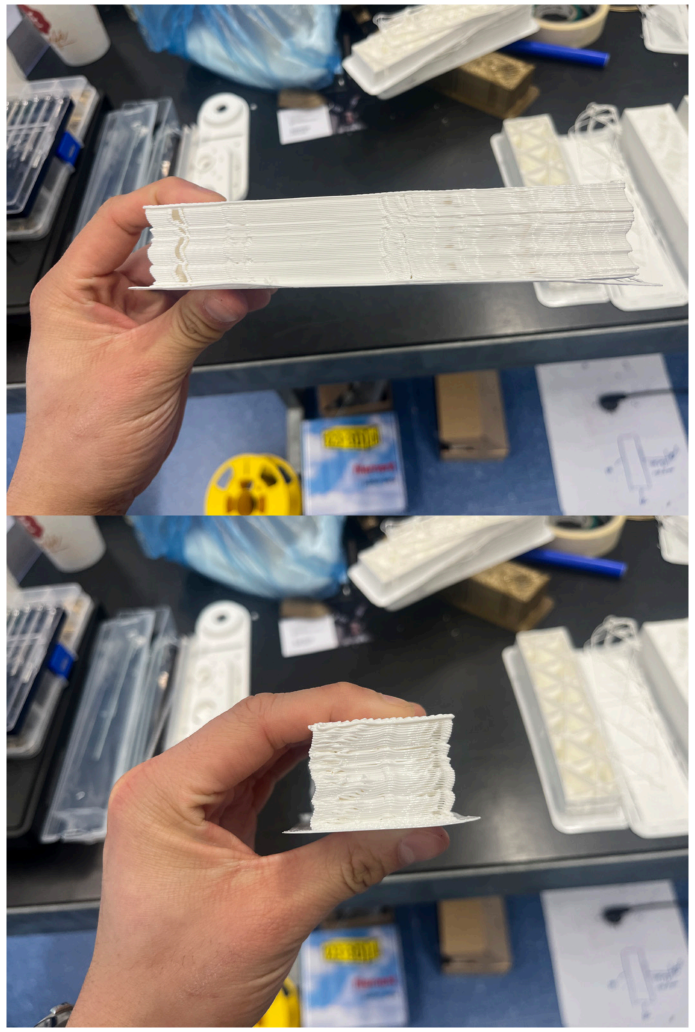


Figure 61: Voxel block printed during test 4, although the acceleration has been reduced, alignment problems occurred creating this wavy pattern in the z-direction.

- Print time: 1 hour and 20 minutes
- Similar results to test 4, with a wavy line in the z-direction

Voxel Print Test 6

Adjustments: SCARA_SEGMENTS_PER_SECOND set to 200

- Print failed
- Same misalignment of the layer as in test 3, but near the start of the print this time (figure 63)
- It did look like the wavy pattern was still noticeable but slightly less aggressive

Voxel Print Test 7

Adjustments: SCARA_SEGMENTS_PER_SECOND set to 200, jerk movement in X and Y to 1, acceleration limited to 500 mm/s, and flow to 110%.

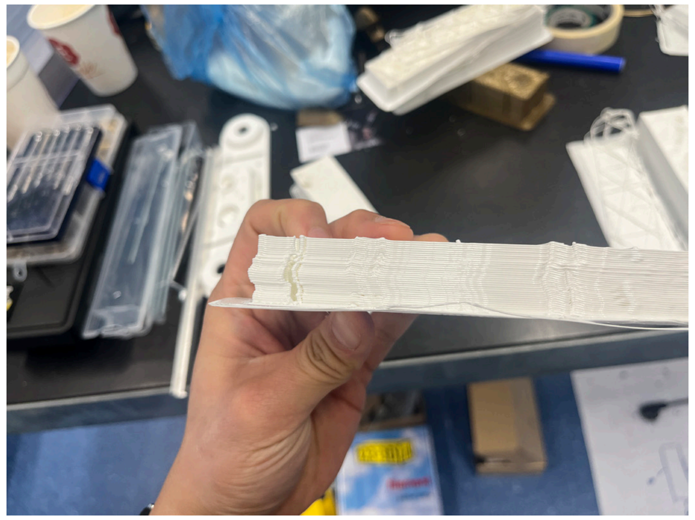


Figure 62: Voxel block printed during test 5, with a similar wavy look due to misalignment of layers in print 4.

These changes are aimed to totally avoid the acceleration issue and also avoid the wavy structure that was observed in print test 4. The testing results seem to indicate that the acceleration issue may be more deep rooted in the firmware, so the only way to deal with it now is limiting it.

Figure 63: Failed print during test print 6, same aggressive misalignment as in print test 3.

- Print time: 1 hour and 54 minutes
- Best print results to date in regards to resolution
- Less aggressive acceleration at the same segments, but still apparent
- Minimal under-extrusion
- First few layers showed misalignment, but self-corrected after a few layers(no wavy structure)
- Almost perfect roof layer with minimal sagging (figure 64)
- Structure was able to withstand the weight of a person (80 kg)

Voxel Print Test 8

Adjustments: Print speed to 50 mm/s.

With the achieved structural integrity and sufficient resolution, the focus shifted towards enhancing the printing speed without significantly compromising the aforementioned factors.

- First run immediately failed due to light clogging
- Print time: 1 hour and 33 minutes
- Structurally sound print, similar quality to test 7 (figure 65)
- Slight misalignment in the first few layers, possibly due to warping
- No noticeable under-extrusion issues anymore

Voxel Print Test 9

Adjustments: Jerk settings in X and Y to 3, acceleration limit set to 750

- At the start, print failed due to light clogging again
- Print failed after 20 minutes due to the misaligned layer appearing again

Between tests 6 and 7, the prototype was tightened at the pulleys, belts, and all connection points to minimize backlash and prevent skipping of steps. This maintenance step was taken to improve the overall performance of the printer and to find the optimal settings for the desired results.

The print tests revealed a mix of improvements and challenges in the printer's performance. The adjustments led to better layer adhesion, reduced under-extrusion, and improved structural integrity. However, some issues persisted, such as acceleration at specific segments, occasional layer misalignment, and clogging of the nozzle.

Most of the issues mentioned before could be improved by using better components such a more high end nozzle and extruder, but also printing the embodiment on a better 3D printer to minimize backlash. The biggest issue that keeps happening from time to time, is the sudden misalignment of layers. Which could be the shoulder pulley skipping a step all of the sudden, but is not verified yet. When doing the voxel stacking test, this phenomenon must be observed more closely. If isn't caused in the hardware, the firmware must be the issue which can be a more critical error. The same goes for the sudden acceleration of segments, upon observation it seems likely that this is an software bug. For further research, this problem must be dealt with before expanding into different designs or upon the existing firmware.

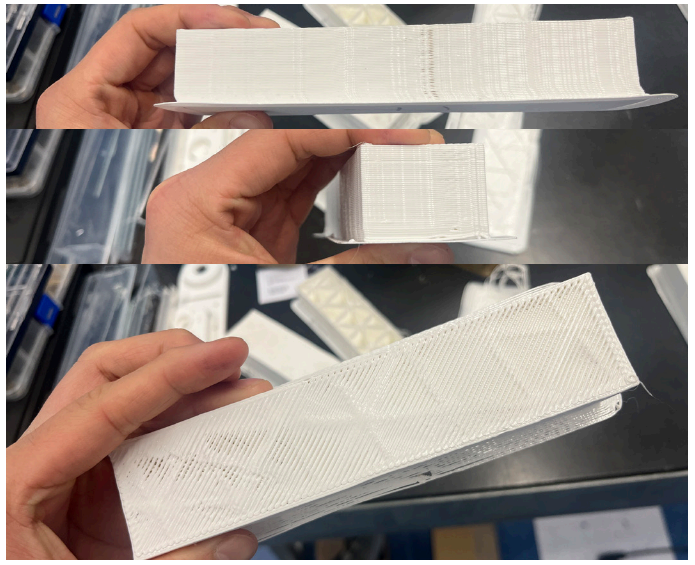


Figure 64: Various angles of the printed voxel during print test 7.

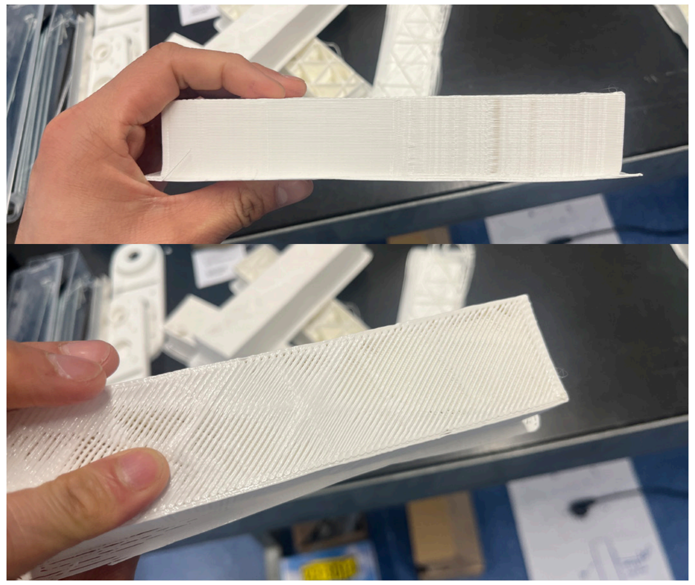


Figure 65: The results of print test 8, which has similar qualities to the results of test 7.

As previously mentioned the printer does have a bit of backlash, but also some flex in the links. It was observed that this flex in the vertical direction was quite beneficial at times. The printer has only been leveled at the center of the bed, instead of mesh leveling on each corner of the print area. Which would produce better performance, but in a more unrealistic setting. This caused the nozzle to 'crash' into the print at times due to the uneven table surface used in the tests. This vertical flex acted as a sort of suspension system, giving the nozzle and arm the ability to 'bump' over some of the obstacles while still printing. This is quite an interesting insight, as some sorts of suspension system could be interesting for a printer that has to deal with uneven surfaces.

The printed voxels were accurate enough to stay above the 95% percentage. This is more than enough accuracy preventing the necessity to overprint to guarantee voxels that are wide enough for the robot to climb on. You can see the averages in table 6.

Compression test

In the proposed use cases, resolution is not as important as the structural integrity of the prints. To get a rough idea of how the SCARA printer's voxels perform relative to the same voxel printed by a conventional printer, a simple compressive test was done. The most important feature is that it must be able to be fully supported by its own prints. The voxel that was printed during the 8th test run was used for the test, while another voxel was printed using similar settings on a Ultimaker 2+ printer. To perform the test, a compressing machine was used. Due to the larger surface area of the voxels relative to the load cells of the machine, 2 steel plates were used to disperse the force evenly over the whole surface. The machine then pushes the two plates together and therefore effectively compressing the voxels(figure 66). The strain is then measured and set against the compressive force in a graph. The stress strain curve is an industry standard that showcased the phases of a material before failing. The load cell was only able to go up to around 9 kN, at that point the machine resets itself. In the end the results were quite surprising. The voxel printed using the Ultimaker reached yield at around 8 kN and fracture happened quite soon after(figure 65). The voxel that was printed using the SCARA setup

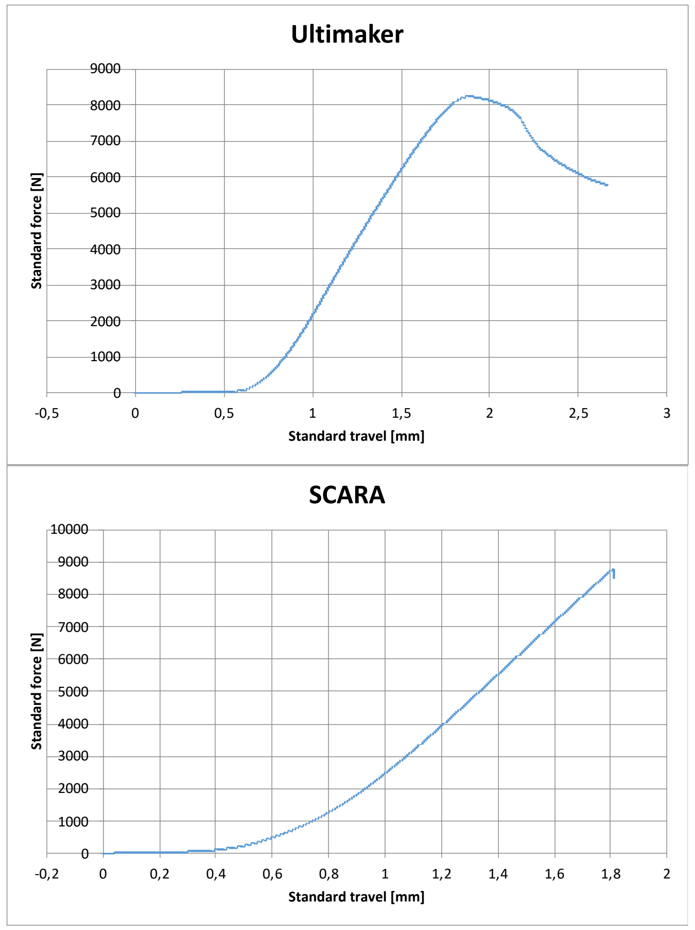


Figure 65: Results of the compression tests visualized in stress-strain curves. The top graph is the voxel printed by an Ultimaker 2+ and the bottom one is the SCARA printer.

Voxel #	Accuracy in X	Accuracy in Y	Accuracy in Z	Average Accuracy
1	99,38%(+)	97.70%(-)	97,22%(-)	97,10%
2	99,79%(-)	94,57%(-)	98,41%(-)	97,59%
4	99,58%(-)	96,66%(-)	98,14%(+)	98,13%
7	98,33%(+)	95,58%(-)	97,68%(-)	97,20%
8	98,02%(+)	94,27%(-)	99,52%(+)	97,27%
Ultimaker 2+	99,75%(-)	99,43%(-)	99,51%(-)	99,56%

Table 6: Results of the accuracy measurement of the successful printed voxels.

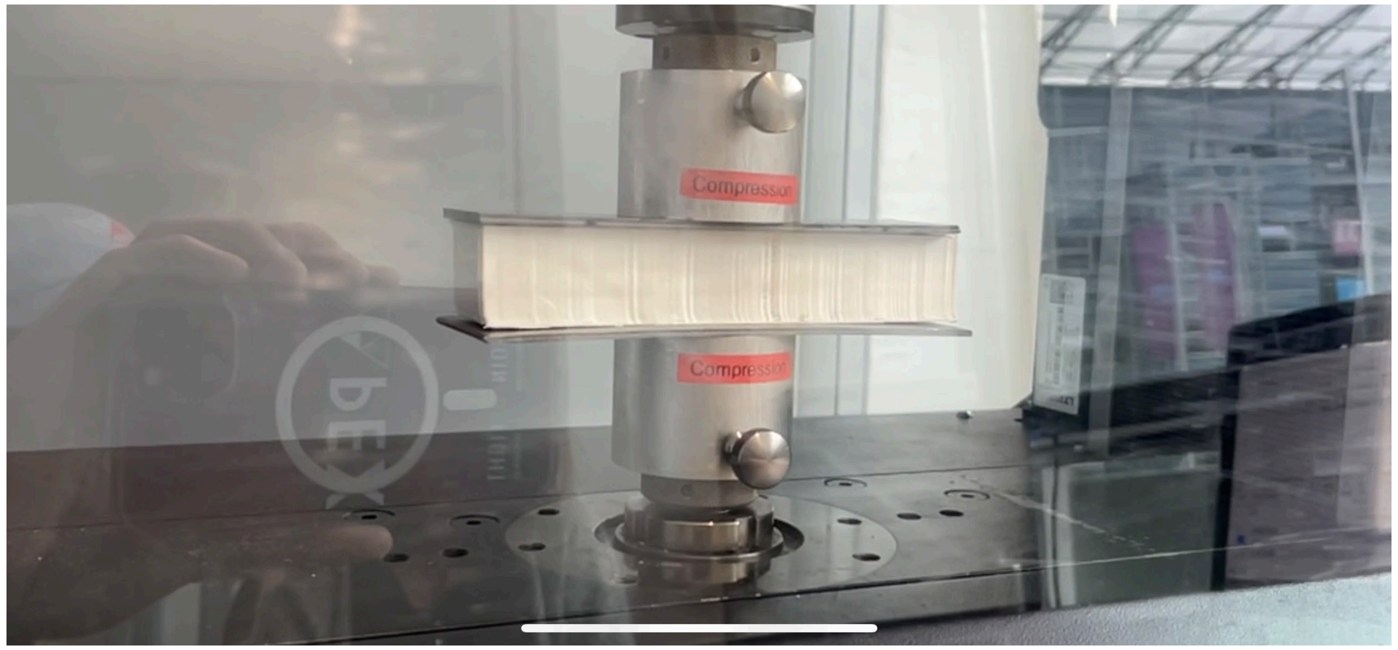


Figure 66: Compression testing of the printed voxels, wherein two steel plates were pressed up against the voxels.

never fractured, it was able to the limit of 9 kN at which the machine stopped itself (figure 65). More precise testing can be done to find the exact yield and fracture point, but this is enough prove the structural integrity of the printed voxels for ts purposes. Again, important is too do similar testing again when scaling up as that may produce different results. Another critical factor that should not be overlooked, is the fact that the SCARA printer does not produce consistent results yet. Some prints may differ in qualities.

Voxel stacking

The final test that was required, was to prove that the voxel based stacking strategy would be feasible. Previously, a test using a smaller scale on a conventional Ender 3 V2 printer was done which produced promising results (figure 67). That test was also done with no heated bed and all of the voxels were printed in place (not moved afterwards). The largest distance that it was able to bridge was 15 mm, no larger distances were tested.

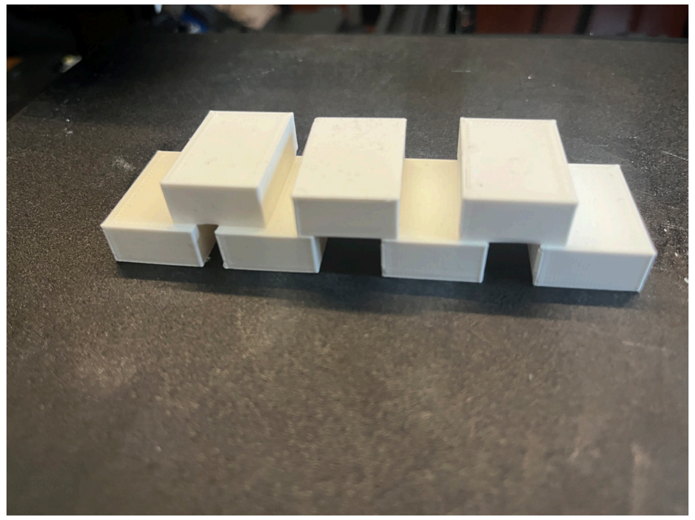


Figure 67: Small scale test of the voxel stacking strategy, done on a Ender 3 V2 printer with no heated bed.

In the full-scale test, a procedure almost identical to the previous one was employed, with the only difference being that the SCARA printer had to be manually moved to print the voxels at an appropriate distance from one another, due to its limited build space, replicating having a mobile platform in a way. Important to note is that the cooling fan was not originally supposed to be used, the current hot end mount makes it so that the cooling fan bulges out at the ‘front’ of the arm. With the cooling fan mounted, it meant that the printer was only able to print the next voxel at a minimum distance of 20 mm from the first one to not crash into the previous one. The issue was avoided by forcefully turning the cooling fan to the other side and consequently bending a part of the mount(See figure 68). The design must be adjusted in the future.

And so a first voxel was laid down, the SCARA printer was then repositioned and another voxel was placed 20 mm from the first voxel (see figure 69). After which, the SCARA printer was repositioned again so that the nozzle was able to reach the middle of the gap between the two voxels.

Figure 68: The cooling fan is forcefully turned to the side of the shoulder so it does not clash with the previous voxel.

The same G-CODE was then applied to print the final voxel, only this time placing it 15 mm above the surface. The outline will be the easiest segment for the printer to bridge, the first 2 infill layers will be the most challenging section as was observed in the small scale test. As predicted, printing the outline in between the 2 voxels was not an issue. The first infill layer did not seem too difficult either(see figure 70). Only 4 strings disconnected from one edge (one side) at the very end which was not critical. In figure 70 you can clearly see the infill pattern connecting neatly between the gap. Following a successful initial infill layer, the remainder of the printing process was relatively straightforward for the SCARA, given that a solid foundation had already been established.

In the end a successful 3 stack voxel structure was printed in around 2 hours time(figure 72). Good to note is that the voxel dimensions had been altered to 40 x 160 x 15 mm to reduce testing time. The final structure adhered well to the bed and together, it printed the voxel with adequate resolution while maintaining structural integrity. The system had no clogging or alignment issues inbetween the prints, it was abe to print the 3 voxels right after each other. These voxels used identical parameters as the voxel that was used in the compression test. All though different dimensions may vary its property every so slightly.

Summary of Results

In summary, the voxel print tests provided valuable insights into the performance and capabilities of the SCARA 3D printer. Through a series of iterative adjustments and improvements, the printer demonstrated significant progress in print quality, structural integrity, and efficiency. However, some challenges remained, requiring further investigation and analysis to fully optimize the printer’s performance.

The test verified that using a voxel based strategy increases the speed of the building process, aside from having to print less material, it also gives the ability to fully optimize the print settings for that specific voxel block. Current-

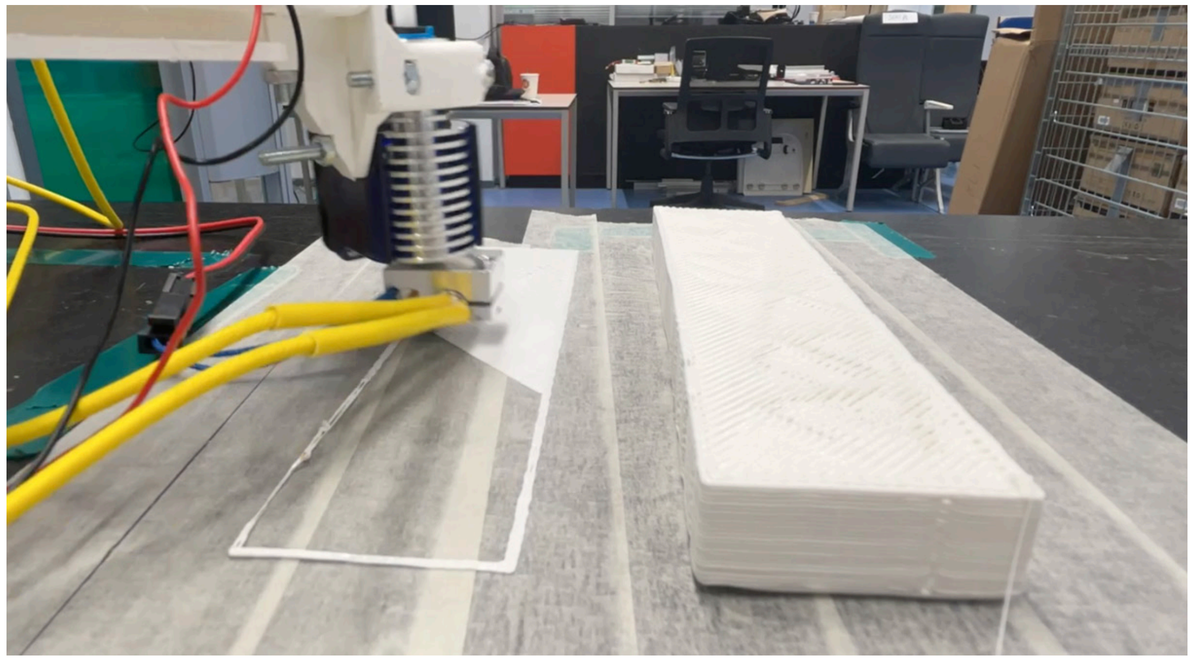


Figure 69: Screen shot of the timelapse of the second voxel printing during the stacking test. The second voxel was placed approximately 20 mm away from the first one.

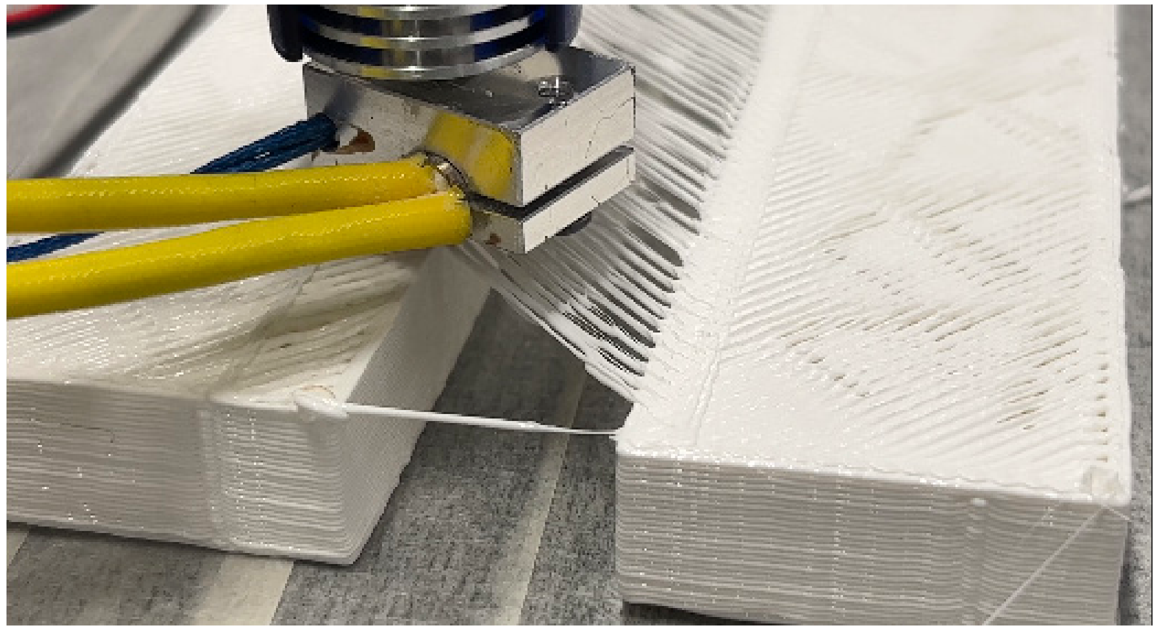


Figure 70: The most difficult layer to print with the overhang, the first infill layer. The connection with the surface of the 2 voxels is key for the material to stay up.

ly the printer is able to provide a solid voxel in 1 hour and 33 mins. The printer still has room to further optimize and reduce that print time, but given the context further optimization does not add to the research. The real question is if conventional FDM printing is the correct technique to use for further iterations, given resolution is not of utmost importance and scaling issues. More on this in the next chapter.

The compression test highlighted that the proposed design may print structures that are structurally stronger than your conventional printers. This is probably caused by using larger diameter nozzles which effectively means extruding more filament. More importantly, it showed that at this scale it can easily print structures that are able to support itself fully.

The voxel stacking tests were successful in showing its feasibility but also its effectiveness. Without optimizing any parameters it is able to bridge a relative large gap of 20 mm without any notable problems and still has potential to bridge even larger gaps.

All of the testing showed promising results. Additional testing and experimentation must be done to further optimize the different proposed processes. No more testing was done simply due to the time constraints, there was still potential for further optimization as the system did have some consistency issues.

General observations were made in regards to the current design and material choice. Some of the design choices were limiting the functionality of the proposed system. For example, the placement and material of the component on which the shoulder stepper is mounted on, is not rigid

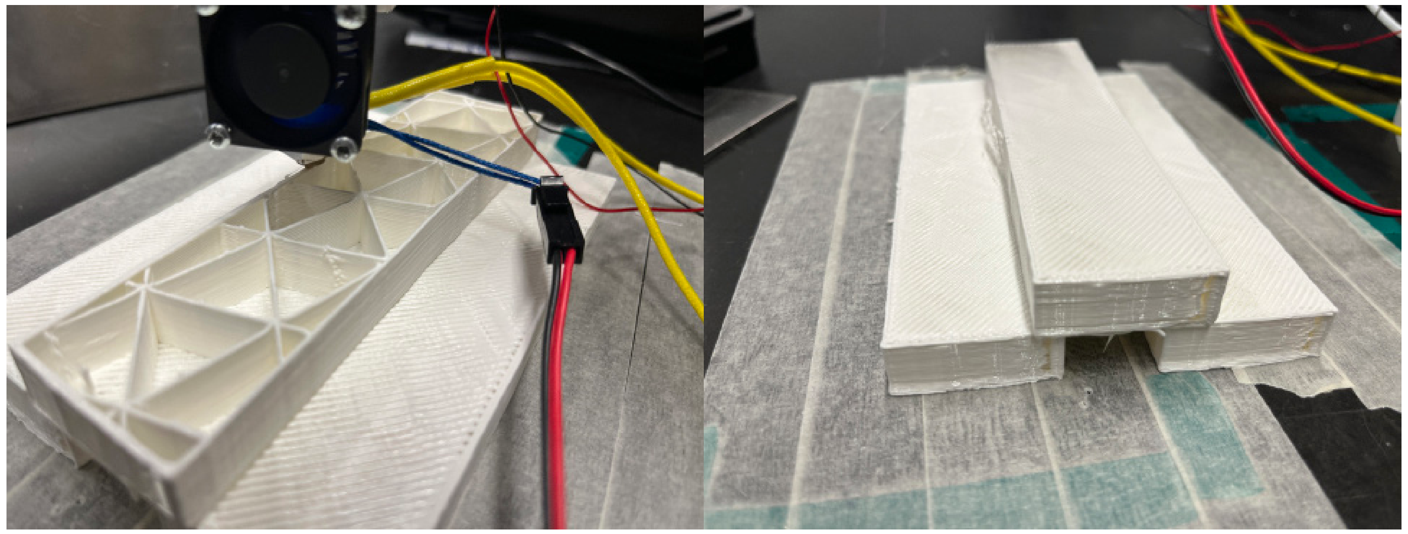


Figure 72: Succesful stacking test of 3 voxels that took approximately 2 hours.

enough. The belt and pulley system is pulling on the shaft of the stepper causing a slight bend of the component (see figure73). In general there was still some play and backlash in the printer. The hypotheses currently is that the inconsistencies found during testing are a mechanical fault. The tension on the belts are shifting over time with the current setup. Improving rigidity by using different filaments, adding support structures and replacing some components with the off the shelf ones can all drastically improve the system.

In the next chapter, a more in-depth discussion of the results will be provided, focusing on the implications of the observed challeng-

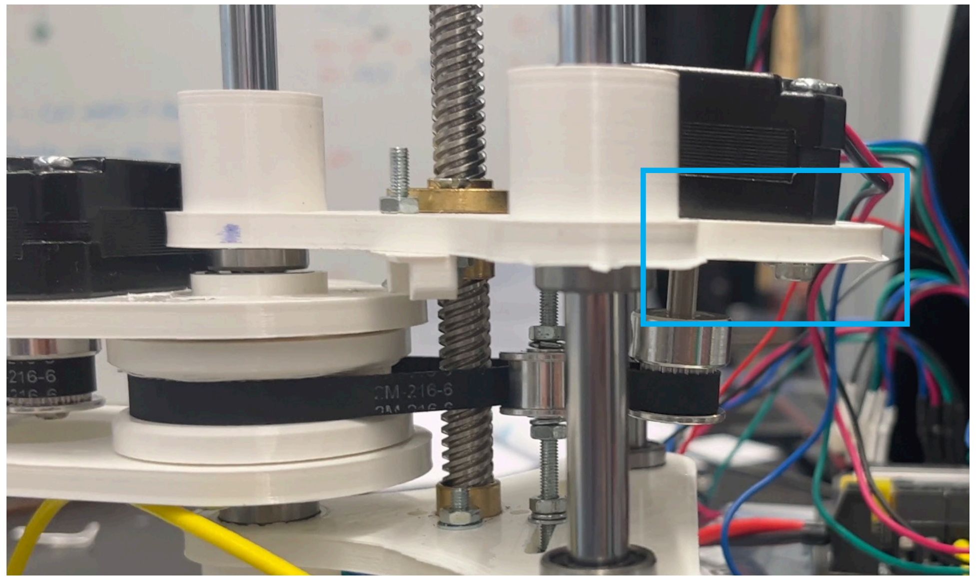


Figure 73: Slight flex of the stepper and its mounting surface due to the belt and pulley system, the pressure is caused by the tensioner bolt.

7 Conclusions & Discussions

In this chapter, the results of the prototype, implications of these results and the value of mobile robotic swarm builders in the given context will be further discussed. Additionally, limitations of the current work will be used to propose recommendations for future work on this subject. Finally, potential use-cases and contexts for the proposed final design will be presented.

SCARA 3D Printer

Achievements

The results indicate that SCARA mechanism based 3D printers can be implemented while having adequate performance. SCARA-based systems offer great potential for mobile robotic builders, as demonstrated by our prototype, which features a compact design and a relatively large work area. The system lays down the groundwork for future builders by integrating off the shelf components into a functional bare bones lightweight design. While its climbing capabilities have not been tested, it provides valuable insights into a potentially promising segment of mobile 3D printers.

The design of the SCARA printer integrates several features that focuses on creating a design that is highly customizable and adaptable. The firmware is can be easily adjusted to be used with different type of SCARA movement systems. For example, using SCARA printers with or without intermediate pulleys and a left hand or right hand system. The design implements embodiment components that are fully printable on most conventional sized printers. The flex in the system is also used as a suspension system to help in printing on uneven surfaces. Although a quite rudimentary system, it still showcased many benefits during printing. The design also adds tensioner pulleys and open face slots to make assembly relative easy. Using only off the shelf components and parts that are printable on most mid-sized consumer 3D printers, making it an accessible system for potential future users/researchers.

The design also proposes a voxel-based approach for printing traversable structures for robotic swarm builders. This voxel based approach reduces printing time, discretises the building process and strategy, and simplifies the system as a whole. Additionally, it gives the ability to fully optimize the printing mechanism for its specific voxel design. This also means that certain components and settings can be omitted to reduce weight and firmware complexity. The voxel-based approach was also experimentally validated and evaluated.

This project delivers a detailed design and physical prototype of a printing mechanism that has the potential to be utilized for a mobile robotic builder. The design integrates all aspects necessary to deliver a fully functional compact printing system, including mechanical design , an electronics system and software. All of these aspects will be made open source and can be found on the following github page:

https://github.com/MigraineMonster/SCARA-Printer-for-Swarm-Robotics.

The capabilities of the proposed printer mechanism was experimentally validated and evaluated during this project. Many insights were gained into the potential of the system but also the drawbacks. These insights will be important for future researchers to further improve this concept.

Challenges and limitations

The results has highlighted one major flaw in the current prototype, the printing speeds that the system is able to achieve are slow in the context of construction. In a realistic scenario, larger constructions would take painstakingly long to be built. However, there is still a lot of room for improvement in this prototype. Rigidity can be improved by using a different manufacturing process than 3D printing, which is suitable for rapid prototyping but does not posses the best material characteristics. A more rigid system gives more room to increase the speeds without losing the quality. To improve the performance in terms of power, one potential solution is to use more powerful stepper motors. However, it is important to note that this must be combined with improvements to rigidity or design adjustments to ensure that the elbow stepper motor is not placed on the arm. Furthermore, as resolution is not a major concern for a robotic builder increasing nozzle diameters(even more than the 0.8 mm currently used) can increase printing speeds more. Even looking at other types of filaments which can deposit more volume is a viable option. Also, while this projects focuses on a single builder, it must not be forgotten that the goal is to have a fleet of these builders working together which can significantly improve the build time. FDM printing was selected in this project due to the accessibility of it and its open source community. This made it possible to rapid prototype and test. If the developments of FDM printing does not reach the required speeds for such a system, there is still an array of different similar methods of deposition systems. Concrete printers for example are a great option, the only major flaw is the storage system.

A significant limitation of the FDM system used in the prototype is its requirement for a nearly level printing surface. While minor inconsistencies can be overseen by simply depositing more material or using a probe system, no printer exists yet that is able to print on extreme uneven surfaces. Although it can be argued that construction typically involves laying down a level base layer first, this approach would limit the potential use cases for the system. The current probing technology performs quite well, even when using low-cost probes. The issue at hand is that these probes need to measure the surface beforehand, to then adjust the z-offset at different portions of the ‘print bed’ accordingly. Implementing some sorts of live leveling/probing system is necessary to be able to print ‘everywhere’. However, when dealing with larger height differences, it becomes crucial to define a starting point that offsets can be relative to. This is especially so when working with G-Code and pre-defined voxels. The before mentioned ‘suspension system’ that is achieved by having a certain amount of flex in the links also has potential to be helpful in this leveling aspect by giving the nozzle more margin to make mistakes. Further research in this area is necessary to fully explore and address these issues.

For innovation, it can’t be expected that such novel systems would overtake the construction process instantly. In a more realistic setting, such machines would be tested and placed in construction sites where the majority still consists of human workers. A challenge can be found in integrating such autonomous systems in the current construction process. The current concepts consists of a low level controlled robot that simply builds if it can, it does not know or have a final construction in mind. When the goal is to reach a certain point or build a structure of a specific volume, then this method should be sufficient. But when looking at larger construction sites, wherein the robots also have to cooperate with human workers, this proposed low level control system will have problems integrating in the current process. In a construction site where only these types of builders are used, a higher level of control is often still necessary for efficient operation and desired outcome.

Implications of the research

In the broader context of implications, the design of the SCARA 3D printer brings the research of termite-inspired swarm robotic systems to the next state. Termites are able to construct complex and large structures while using basic behavioral rules. Meaning that this collaborative effort is done by numerous agents without the need of a centralized control unit. These termites are able to build in a variety of ways by combining dirt and their saliva, a process that is analogous to additive manufacturing. By replicating this biological example, an interesting method of construction can be derived, a decentralized automated manufacturing process using additive technology. This approach can significantly improve efficiency, flexibility and adaptability in building processes. The swarm, in theory, is able to overcome unforeseen challenges and obstacles while also covering vast areas quickly. The research contributes to this field by demonstrating the potential of implementing mobile and compact 3D printers for swarm robotic systems.

The implications of mobile robotic builders and swarm robotics in the construction industry specifically are huge. The proposed method focuses on improving construction efficiency, safety and even sustainability in some ways. With this method the end-users, the workers and also the environment can benefit from it. By exploring the potential of these mobile robotic swarm systems the project contributes to address the various challenges that are currently apparent in the construction industry.

This project also advances the more obscure SCARA 3D printing machines. Even with the many different benefits of using a SCARA system such as compact size, relatively large build space and potential for higher accuracy, the system is not as widely used in 3D printing. Cartesian and Delta printers appear to be the majority of current printers on the market. The complexity, higher costs(due to the complexity), lack of firmware support and limited resources are all factors that hinder this type of system. Our work in the firmware gives a solid foundation for future SCARA machines, the firmware is highly adjustable to various types of SCARA mechanisms. The bare bone approach to the design creates a good base model that is relatively cheap to make and easy to build. By making all of the resources open source we hope to further advance this 3D printing technology.

This research paves the way for more mobile 3D printing systems. Although our project has not yet achieved mobility or climbing capabilities, the successful development of the SCARA 3D printer provides a solid foundation for future research in these areas. Our design provides a relative simple method of climbing, same to the system used by TERMES. What is unique to the design is the leveling system that makes it possible for the system to print in awkward angles. This is the first step towards highly mobile 3D printing systems.

Future work & recommendations

The scope of this project was to focus on a singular mobile robotic builder. Even-though the mobile platform was implemented in the design, due to time constraints, only the printing mechanism was able to be prototyped and tested during the research. Simultaneously, tremendous work has been done in regards to the control systems of such swarm robotic fleets by peers. This project was focused on the design of such a singular robotic builder, but with the robotic swarm strategies in mind.

Although this research was unable to obtain results regarding the mobility of the system, prior research has already demonstrated significant potential in this area. The TERMES project (REF) for example, it was able to successfully design and produce a system that is capable of building and climbing. In addition, while our research focused on simplifying certain aspects due to integration challenges, there are many current projects that have already showcased remarkable features related to climbing, balancing, and mobility in robotic systems. The most recent example being Boston Dynamics and its various robotic designs.

The research has led to some important insights that needs to be well considered in future work. The 3D printing speed and capabilities are the largest hurdle for a feasible design. It is important that a human counter part using traditional constructions methods must not be marginally faster than our robotic counter part. While it still has the benefits of being a more safer and automated process, there is a significant lower chance of such systems being implemented when its too slow. However, the small scale prototype is not directly comparable, as previously mentioned scaling comes with many challenges (and changes). So it is good to think about the speed of the system, but also to remember that comparison must be done at a later stage. There are many other interesting forms of additive technology such as cement printing that has great potential in this context. This design opted to use FDM technology due to its being easily accessible, but future work should definitely look into other techniques.

Another major hurdle in integrating such systems into the current construction processes resides in the safety concerns. Slight errors could be fatal in the future. Where concrete printers are overseen by many human operators and are focused on one structure, this system proposes many individual systems that are automated. Our systems must be able to build structurally strong constructions while moving, climbing and navigating. There are a lot of factors which increases the chance of mistakes being made. Systems and strategies must be further designed with this safety factor in mind, to be able conceptualize realistic systems.

The current design focused on creating a compact and mobile system using a relative small power supply. The power supply is plugged into the power socket. For a truly mobile system a different type of power is necessary. Batteries and converter modules are necessary to power the system and make it chargeable. In the appendix a simple system layout is suggested for a mobile system using batteries. It should especially be feasible without a heated bed which consumes most of the power of printers, but research must be done to verify this and get the data.

The scalability of our design, and swarm robotics in general must be tested properly. While similar systems already show they are able to work together, it is important to verify that larger builders are able to do the same. Using 3D printing technology is great for the scale that we are currently using, but significant larger robotic systems must be designed to be somewhat feasible in building human sized constructions. Simply making the ‘printer’ larger will not suffice for the FDM method, various factors make it hard to scale up 3D printing currently. A more easily scalable system or refined 3D printing system must be explored in the future. As previously mentioned, conventional FDM technology may not be the answer.

In general, some design aspects of the SCARA printer should be improved for better performance. While it is a functional design, it still performs inconsistently likely due to the mechanical side of things. Looking at implementing more off the shelf component or using better materials can already enhance a lot. Also improving the design to make it even more easy to assemble and disassemble can help the system to be more accessible and therefore easier to further develop in the future.

Potential use cases

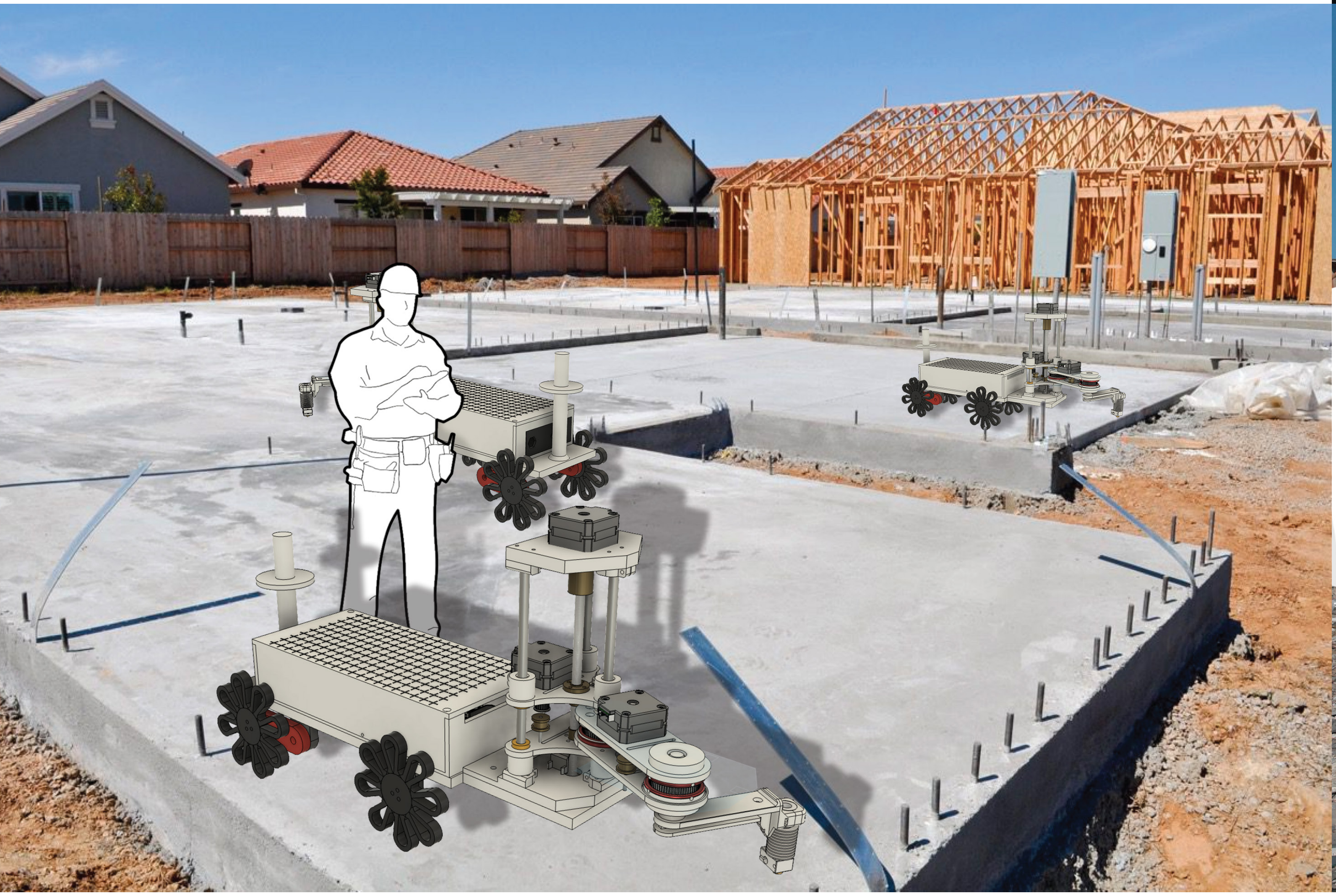
The project can help advance the construction industry immensely in various ways. In very large-scale construction projects our builders can drastically reduce construction time and labor costs, given that the system is scaled using a material that is fit for construction purposes. Projects that include building infrastructure, residential complexes and commercial buildings can take enormous amounts of time and money. The concept of swarm robotic builders is based on the idea that robots can work in parallel, covering large areas quickly and efficiently. When implemented correctly, this approach could potentially alleviate the pressure of various construction projects. Imagine this fleet of robots laying down the foundation of these larger complex buildings while the workers can focus on the more detailed parts of the construction. Humans and robot could work together, if not have the robots finish up the more mundane and simple structures. A lot of advancements need to be made in filament choice and mobility in this design for it to be able to reach that level, but nothing impossible. The increasing use of construction technologies such as concrete printers indicates that the idea of mobile 3D printers is not far-fetched. As these technologies continue to develop, it is likely that mobile 3D printers and larger concrete printers will cross paths and evolve together, presenting new opportunities for construction automation.

In disaster-stricken areas the swarm builder are able to assist by reaching areas that can be hazardous or are obstructed by debris and other obstacles. The swarm robotic builders can be a powerful tool for disaster relief efforts, as they can quickly construct structures in hard-to-reach areas and create support structures for unstable environments such as collapsing tunnels. Additionally, they can be used to build simple infrastructures and shelters to improve living conditions in disaster areas. Overall, the mobility and parallel capabilities of these builders make them a valuable asset in improving and repairing damaged environments. Again, the builders are also able to cover large areas relatively quickly which could even be of help in regards to search and rescue. Our current design does not support that but simple modifications could be added. The major hurdle in employing these type of builders in disaster areas is that human lives could be at stake, wherein the proposed low level control system may be beneficial in the context of construction, it may be an unsuitable option when it comes to rescue.

A huge benefit of using FDM-like construction methods compared to more traditional methods, is the fact that it is highly precise and customisable. Wherein more traditional methods needs adjustments and more time to build more complex and customised architectural designs, FDM-like methods should in theory be able to instantly deliver those needs. Mobile robotic builders can help innovate and bring more intricate designs to life by implementing 3D printing processes into construction. Where concrete printers have laid down a great basis for robotic builders in the future, different types of materials and sizes of these builders need to be explored more.

Another area in which swarm robotic builders can help is sustainable and eco-friendly construction. By using environmentally friendly materials these swarms of mobile robotic builders can reduce waste and the human foot print in construction areas. By requiring less or no construction workers it can also be argued that energy consumption of construction processes can be reduced as these swarms could in theory cooperate together more efficiently than humans. Less infrastructure needed for various machines and transport, less humans on the worksite and therefore also less site amenities such as temporary housing, break rooms and storage facilities. These swarms could reduce the overall footprint of construction sites. Major advancements needs to be made in the building process for this to work, the critical point can be found in building vertically.

And the most straightforward use case would be to use the mobile swarm approach to do 'regular' 3D printing. Having these mobile robotic builders means that larger structures could be printed without needing large crane like systems such as the cement printers. The mobile swarm approach can reduce print time for larger structures significantly by allowing parallel printing by several agents. And depending on the amount of builders, being able to quickly print larger structures 'wherever' that may be.



Conclusion

In the end, the project proposes a system design on which can be build upon further in the context of robotic swarm builders. The research successfully explored the design, development and testing of the SCARA printing machine. Many valuable insights were gained that highlighted the potential, limitations and challenges of the swarm based robotic builder. This potential will be more obtainable by optimizing and improving the print speed and leveling aspects of the system. Furthemore, some integration challenges must be overcome. In general more research towards various kinds of additive technology can also add a lot of value. This project has laid down a foundation for further research and development in the field of decentralized automated manufacturing. Hoping to achieve a similar level of efficiency, flexibility and resiliency as the termites themselves. Swarm strategies can be implemented and tested using the proposed mobile builder, further improving this field. Hopefully this project acts as a stepping stone for a novel way of manufacturing that can enhance and change the landscape of construction.

8 Reference list

1. OAll3DP. (n.d.). The 16 best 3D printer filament types: A comprehensive guide. Retrieved from https://all3dp.com/1/3d-printer-filament-types-3d-printing-3d-filament/

2. All3DP. (2021, January 12). Foam: Lightweight filament – How and why to 3D print with it. https://all3dp.com/1/foam-lightweight-filament-how-and-why-to-3d-print-with-it/

3. Alsoufi, M. S., & Elsayed, A. E. (2017). Warping deformation of desktop 3D printed parts manufactured by open source fused deposition modeling (FDM) system. Int. J. Mech. Mechatron. Eng, 17(11).

4. AMBOTS Inc. (2021, March 3). AMBOTS Swarm 3D Printing [Video]. YouTube. https://www.youtube.com/watch?v=Ruw145U0Lpc&ab_channel=AMBOTSInc

5. Aragawi, G.T.; Zegeye, A.T. (2021). Conceptual design of an autonomous wall-climbing robot for cleaning and maintenance applications. Mathematics, 9, 3160. https://doi.org/10.3390/math9243160.

6. Biront, A. (2022). Design of cellular structures for robotic assembly.

7. Boucaron. (2017). 3D Printers: Remote Direct Drive Extruders Overview [Photograph]. Steemit. https://steemit.com/printing3d/@boucaron/3d-printers-remote-direct-drive-extruders-overview

8. Burns, A. J. (2020). Material Depositing Mobile Robots for Application to Cementitious Additive Manufacturing. The University of Liverpool (United Kingdom).

9. Carey, N. E., Bardunias, P., Nagpal, R., & Werfel, J. (2021). Validating a Termite-Inspired Construction Coordination Mechanism Using an Autonomous Robot. Frontiers in Robotics and AI, 8, 645728.

10. Creality Experts. (n.d.). Creality Hot End Repair Guide [Webpage]. Retrieved 13 March 2023 from https://www.crealityexperts.com/creality-hot-end-repair-guide

11. DK Find Out!. (n.d.). [Image of insect colonies]. Retrieved from https://www.dkfindout.com/us/animals-and-nature/insects/insect-colonies/

12. Donders, E. (2022). Sustainable 3D printing using eggshells.

13. Florian, D., Florian, A. (n.d.). Motherboard. Retrieved January 11, 2023, from https://www.drdflo.com/pages/Guides/How-to-Build-a-3D-Printer/Motherboard.html

14. Global construction market to grow $8 trillion by 2030: Driven by China ... (n.d.). Retrieved October 3, 2022, from https://myice.ice.org.uk/ICEDevelopmentWebPortal/media/documents/news/ice%20news/global-construction-press-release.pdf

15. The Guardian. (2021, February 23). Revealed: Migrant worker deaths in Qatar ‘exceed official figures’. Retrieved January 11, 2023, from https://www.theguardian.com/global-development/2021/feb/23/revealed-migrant-worker-deaths-qatar-fifa-world-cup-2022

16. Klusáček, D. (2019, April 8). SCARA Robot - How to Build Your Own Arduino

17. Based Robot. HowToMechatronics. https://howtomechatronics.com/projects/scara-robot-how-to-build-your-own-arduino-based-robot/

18. Koenig, S., & Kumar, S. (2017). A case for collaborative construction as testbed for cooperative multi-agent planning. In Proceedings of the ICAPS-17 Scheduling and Planning Applications Workshop (SPARK).

19. Marques, L. G., Williams, R. A., & Zhou, W. (2017). A mobile 3D printer for cooperative 3D printing. In 2017 International Solid Freeform Fabrication Symposium. University of Texas at Austin.

20. Mircescu, A. (2021, September 10). x-scara. GitHub. https://github.com/madl3x/x-scara

21. Occupational Safety and Health Administration. (n.d.). Commonly used statistics. Retrieved Month Day, Year, from https://www.osha.gov/data/commonstats

22. Petersen, K. H., Nagpal, R., & Werfel, J. K. (2011). Termes: An autonomous robotic system for three-dimensional collective construction. Robotics: science and systems VII. Chicago.

23. Poudel, L., Blair, C., McPherson, J., Sha, Z., & Zhou, W. (2020). A heuristic scaling strategy for multi-robot cooperative three-dimensional printing. Journal of Computing and Information Science in Engineering, 20(4).

24. Robinson, P. (2019, August 1). Microstepping tutorial: A brief overview. Association for Advancing Automation (A3). https://www.automate.org/blogs/microstepping-tutorial-a-brief-overview

25. Sherline. (n.d.). G-code [Screenshot of webpage]. Retrieved from https://www.sherline.com/g-code/

26. Soleymani, T., Trianni, V., Bonani, M., Mondada, F., & Dorigo, M. (2015). Bio-inspired construction with mobile robots and compliant pockets. Robotics and Autonomous Systems, 74, 340-350.

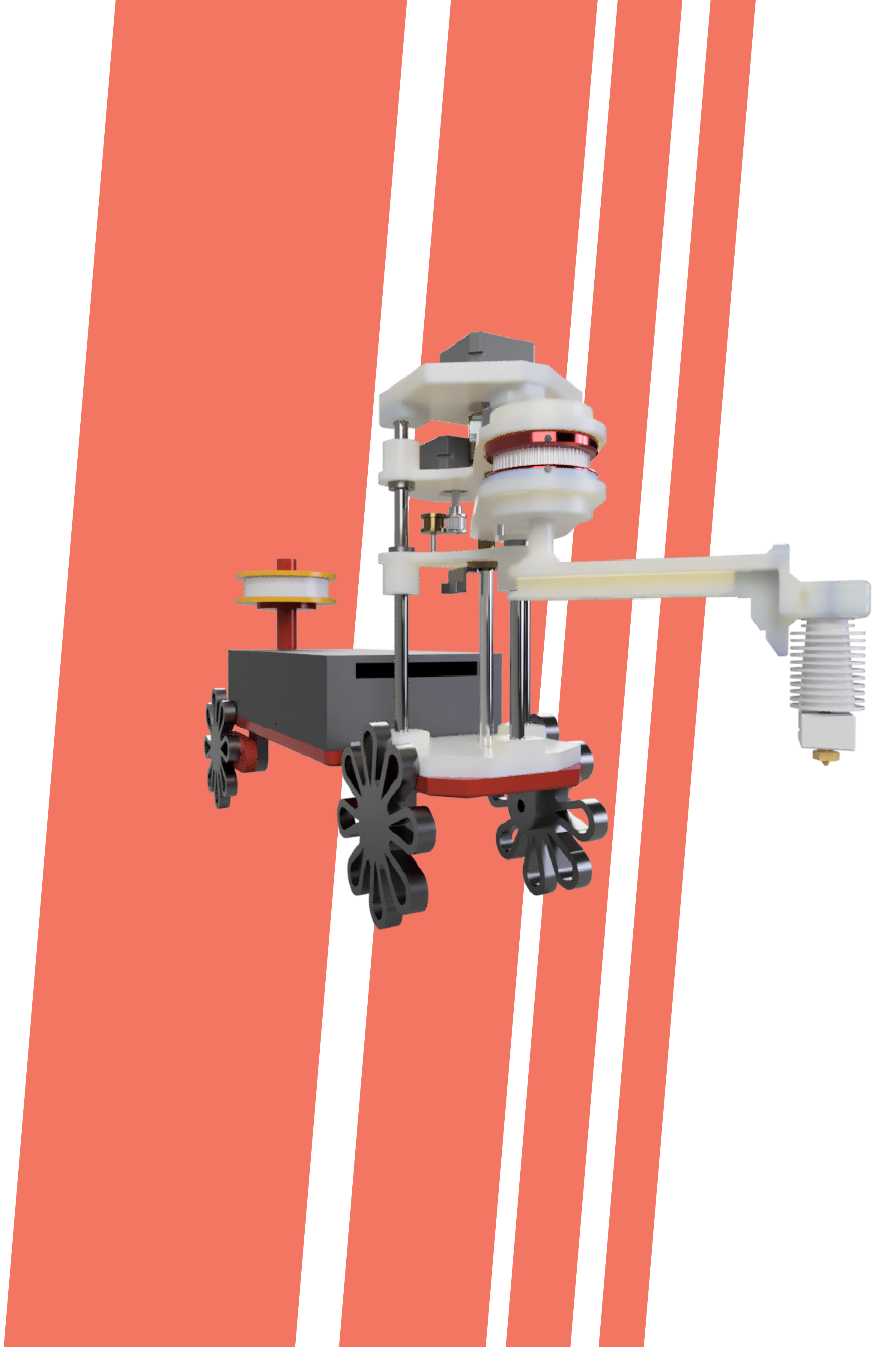
27. Soriano, L. A., Rubio, J. de J., Orozco, E., Cordova, D. A., Ochoa, G., Balcazar, R., Cruz, D. R., et al. (2021). Optimization of Sliding Mode Control to Save Energy in a SCARA Robot. Mathematics, 9(24), 3160. MDPI AG. Retrieved from http://dx.doi.org/10.3390/math9243160

28. Tiryaki, M. E., Zhang, X., & Pham, Q. C. (2019, November). Printing-while-moving: a new paradigm for large-scale robotic 3D Printing. In 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 2286-2291). IEEE.

29. Werfel, J. K., Petersen, K., & Nagpal, R. (2011). Distributed multi-robot algorithms for the TERMES 3D collective construction system. In Proceedings of Robotics: Science and Systems. Institute of Electrical and Electronics Engineers.

30. Williaty (2017, August 7). SCARA 3D printer. Thingiverse. https://www.thingiverse.com/thing:2487048

31. 3Dnatives. (2021, June 21). Zebro Robots to use 3D printing to colonize Mars. Retrieved January 11, 2023, from https://www.3dnatives.com/en/zebro-robots-to-use-3d-printing-to-colonize-mars-210x



Appendix A: measurements of voxel accuracy

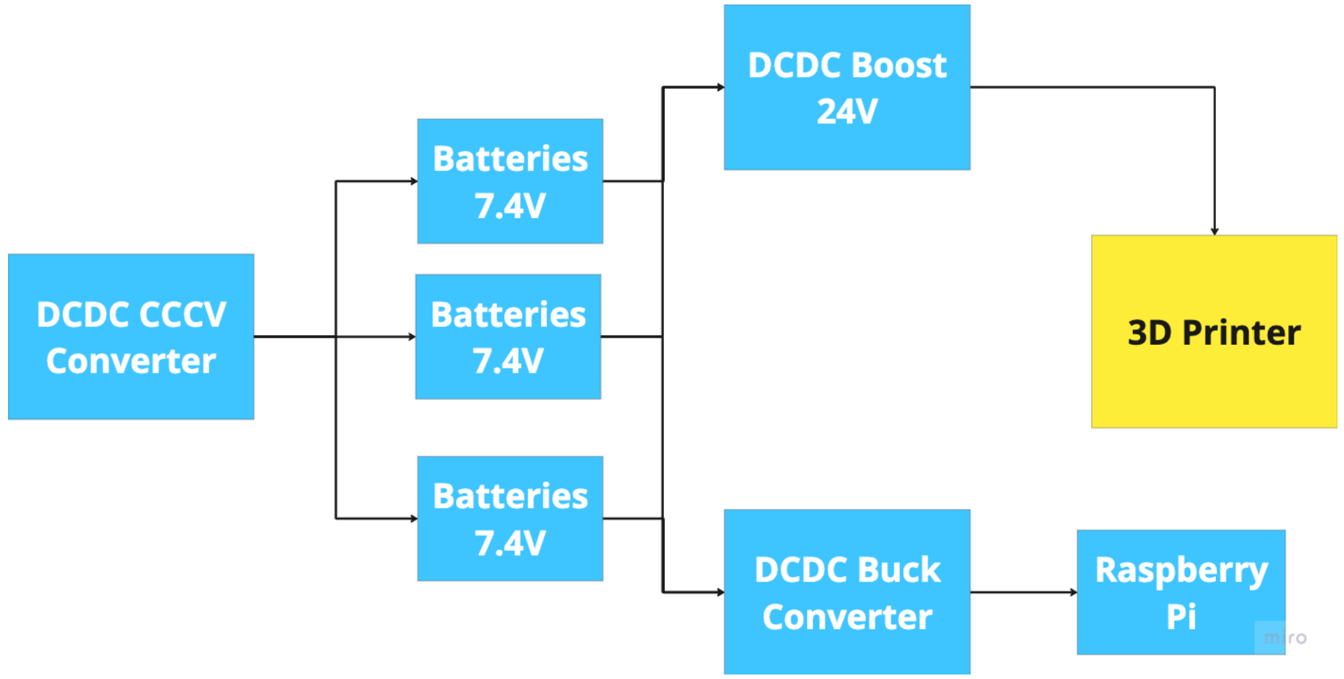
Measurements of each dimension of printed voxels

	Measured dimensions in [mm]			Accuracy in [%]			
Voxel #	**x**	**y**	**z**	**x**	**y**	**z**	**Average**
1	*161,00*	*36,85*	*29,03*				
	160,50	*38,22*	*29,40*				
	161,50	*38,57*	*29,07*				
Average	**161,00**	**37,88**	**29,17**	99,38%	94,70%	97,22%	**97,10%**
2	*161,00*	*37,98*	*29,55*				
	159,00	*37,25*	*30,06*				
	159,00	*38,25*	*28,96*				
Average	**159,67**	**37,83**	**29,52**	99,79%	94,57%	98,41%	**97,59%**
4	*159,50*	*38,69*	*30,77*				
	159,00	*37,87*	*30,53*				
	159,50	*39,43*	*30,37*				
Average	**159,33**	**38,66**	**30,56**	99,58%	96,66%	98,14%	**98,13%**
7	*164,00*	*38,24*	*29,37*				
	162,00	*37,68*	*29,34*				
	162,00	*38,77*	*29,20*				
Average	**162,67**	**38,23**	**29,30**	98,33%	95,58%	97,68%	**97,20%**
8	*162,50*	*37,67*	*30,04*				
	163,00	*36,90*	*30,18*				
	164,00	*38,55*	*30,21*				
Average	**163,17**	**37,71**	**30,14**	98,02%	94,27%	99,52%	**97,27%**
Ultimaker 2+	*160,00*	*39,71*	*29,80*				
	159,30	*39,81*	*29,81*				
	159,50	*39,80*	*29,95*				
Average	**159,60**	**39,77**	**29,85**	99,75%	99,43%	99,51%	**99,56%**

Supposed dimensions

x	y	z
160,00	*40,00*	*30,00*

Appendix B: Schematic sketch of a mobile electronic system



Suggested setup for a mobile and wireless 3D printer. The DCDC CCV converted is used to be able to charge the battery using the same DC input.

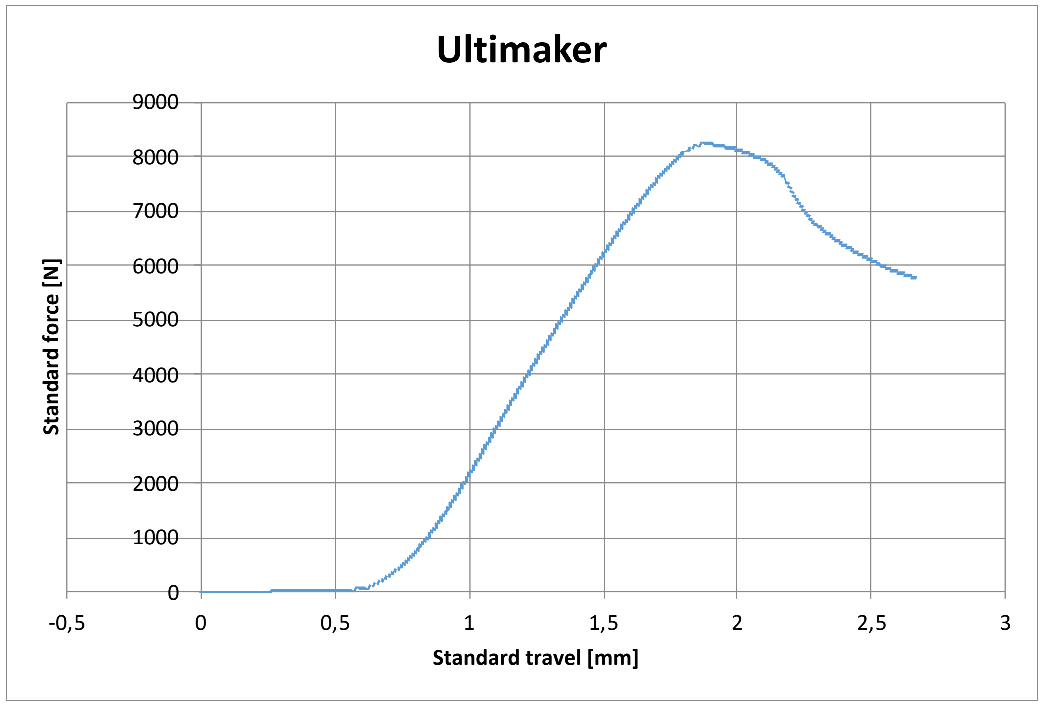
The DCDC boost is obviously for increasing the voltage of the batteries to fit the printer, it has been tested to work with 12 volt systems but the required batteries necessary to use for a 24 v system must be further researched.

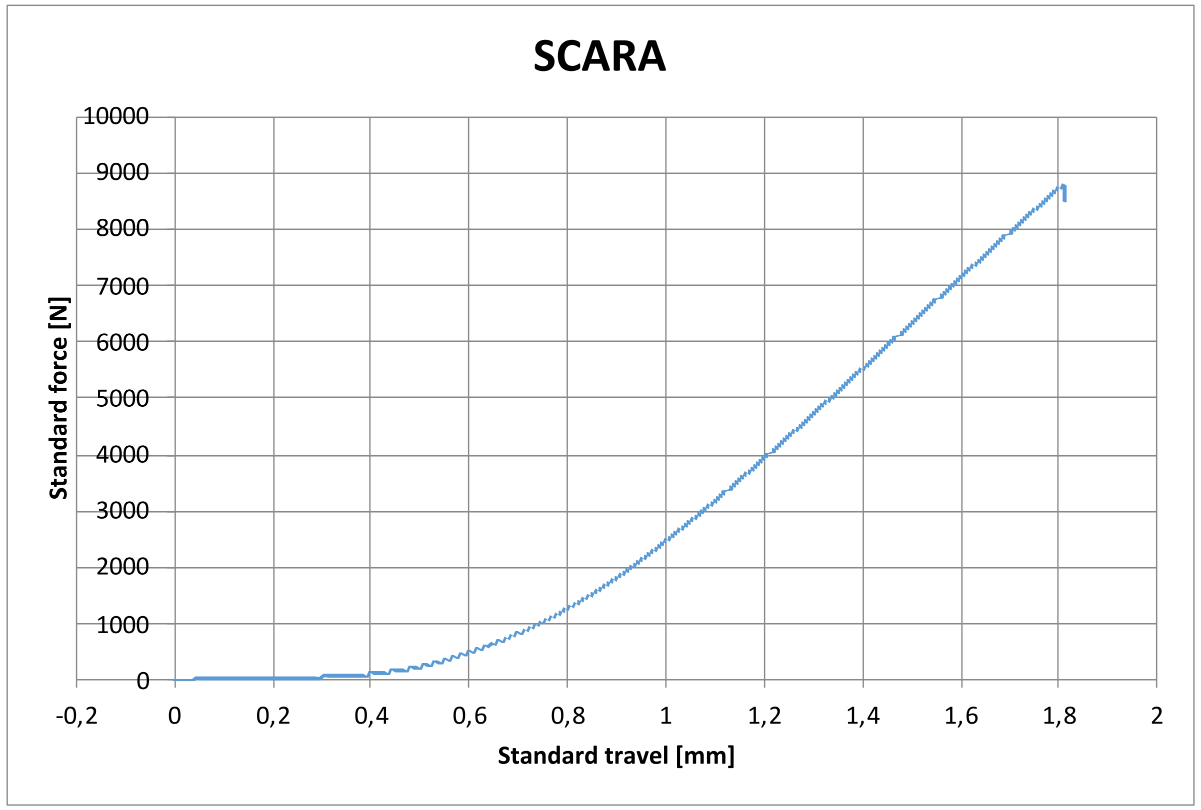
The DCDC Buck converter reduces the voltage to 5 V to be able to power the Raspberry Pi or Arduino to add wireless capabilities.

Appendix C: Results of compression test

	Date/Clock	h_0	F_{max}	dL at F_{max}	F_{Break}	dL at break	W to F_{max}	a_0	b_0	S_0	t_{Test}
		mm	N	mm	N	mm	Nmm	mm	mm	mm²	s
Ultimaker	45055,64	29,8	8235,717	1,892916	5765,098	2,662085	5395,474	39,9	169,5	6763,05	80,762
SCARA	45055,65	30,1	8794,748	1,809759			5129,368	37,9	163,6	6200,44	66,578

Series	Date/Clock	h_0	F_{max}	dL at F_{max}	F_{Break}	dL at break	W to F_{max}	a_0	b_0	S_0	t_{Test}
n = 2		mm	N	mm	N	mm	Nmm	mm	mm	mm²	s
x	45055,64	29,95	8515,232	1,851338	5765,098	2,662085	5262,421	38,9	166,55	6481,745	73,67
s	0,003967	0,212132	395,2948	0,058801			188,1654	1,414214	4,17193	397,8253	10,0296
ν [%]	8,8E-06	0,708287	4,642208	3,176118			3,575643	3,63551	2,504911	6,137627	13,61423





Appendix D: Original Project Brief

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Worang

initials: LB given name: Lorenzo

student number: 4393465

Your master programme (only select the options that apply to you):

IDE master(s): ★ IPD DfI SPD

2nd non-IDE master:

individual programme: - - (give date of approval)

honours programme: Honours Programme Master

specialisation / annotation: Medisign

Tech. in Sustainable Design

Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Jordan Boyle dept. / section: SDE

** mentor: Jun Wu dept. / section: SDE/MF

2nd mentor:

organisation:

city: country:

comments (optional): A chair and mentor from the same section were chosen due to their complimentary skills in computational design and robotic fabrication.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

APPROVAL PROJECT BRIEF
To be filled in by the chair of the supervisory team.

[redacted]

[redacted]

Bio-inspired robotic builders — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 10 - 10 - 2022 06 - 04 - 2023 end date

INTRODUCTION **
Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

In the world of design engineering, many take inspiration from nature. Many living organisms have developed their own complex systems and mechanisms. We try to build new ideas based on these natural phenomena. We are not the only species in the world that know how to build and craft. Many species are capable of building complex structures; birds, beavers and maybe the most impressive one termites. Termites are capable of building tall complex structures that contains different chambers with different purposes(see fig. 1). The ‘royal pair’ has its own loyal workers and soldiers that work together to build these structures. All of these ‘builders’ are working together without any centralized control unit. Basic behavioral ‘rules’ and interaction between themselves and their environment are enough to create these intricate structures.
In the modern world the desire for using autonomous processes keeps increasing. Tasks that are too tedious, complex or even dangerous are streamlined by technology. In the world of construction many dangerous tasks are performed. In the UK most worker fatalities are found in the construction industry according to the Health and Safety Executive 2021/2022 [1]. It has been predicted that the size of the construction industry is to grow to $15.5 trillion by 2030[2]. This growth and risk in the construction industry creates a demand for novel and safe methods to build.
We already see a lot of new systems being designed with the purpose of being more autonomous, faster and efficient. Take for instance the developments that have been made in concrete 3D printing, used to build houses in areas such as Africa(see fig. 2). Houses that can be build within foreseeable time frames and minimal human intervention. A derivative of this concept utilizes a mobile platform combined with an actuated robot arm and its extruder[3]. Essentially a concrete 3D printer with an unbounded build area. Others have focused their work on creating teams of builders that are able to create structures using prefabricated building blocks, traversing said building blocks to create larger structures [4].
To extend on systems that work with prefabricated building blocks, research has been done at TU Delft focusing on robotic builders using lattice structures[5]. All of these projects focused on the lattice system [6], this project hopes to expand the research to a more integrated system.

[1]Work-related fatal injuries in Great Britain. Statistics - Work-related fatal injuries in Great Britain. (n.d.). Retrieved October 3, 2022, from https://www.hse.gov.uk/statistics/fatals.htm
[2] Global construction market to grow $8 trillion by 2030: Driven by China ... (n.d.). Retrieved October 3, 2022, from https://myice.ice.org.uk/ICEDevelopmentWebPortal/media/documents/news/ice%20news/global-construction-press-release.pdf
[3] J. Keating, J. C. Leland, L. Cai, and N. Oxman, “Toward site-specific and self-sufficient robotic fabrication on architectural scales,” *Sci. Robot*, vol. 2, p. 8986, 2017. [Online]. Available: https://www.science.org
[4] J. Werfel, K. Petersen, and R. Nagpal, “Designing collective behavior in a termite-inspired robotconstruction team,” *Science*, vol. 343, pp. 754–758, 2014.
[5]Gawde, P. R. (2021, juli). Modularity in Lattice structures for Circular Product Design Author. Delft University of Technology. http://resolver.tudelft.nl/uuid:b0fc5f9a-b4e1-455a-8bef-1c9a48054d87
[6] Biront, A. (2022). Design of cellular structures for robotic assembly. Delft University of Technology

space available for images / figures on next page

introduction (continued): space for images

image / figure 1: Complex termite structures

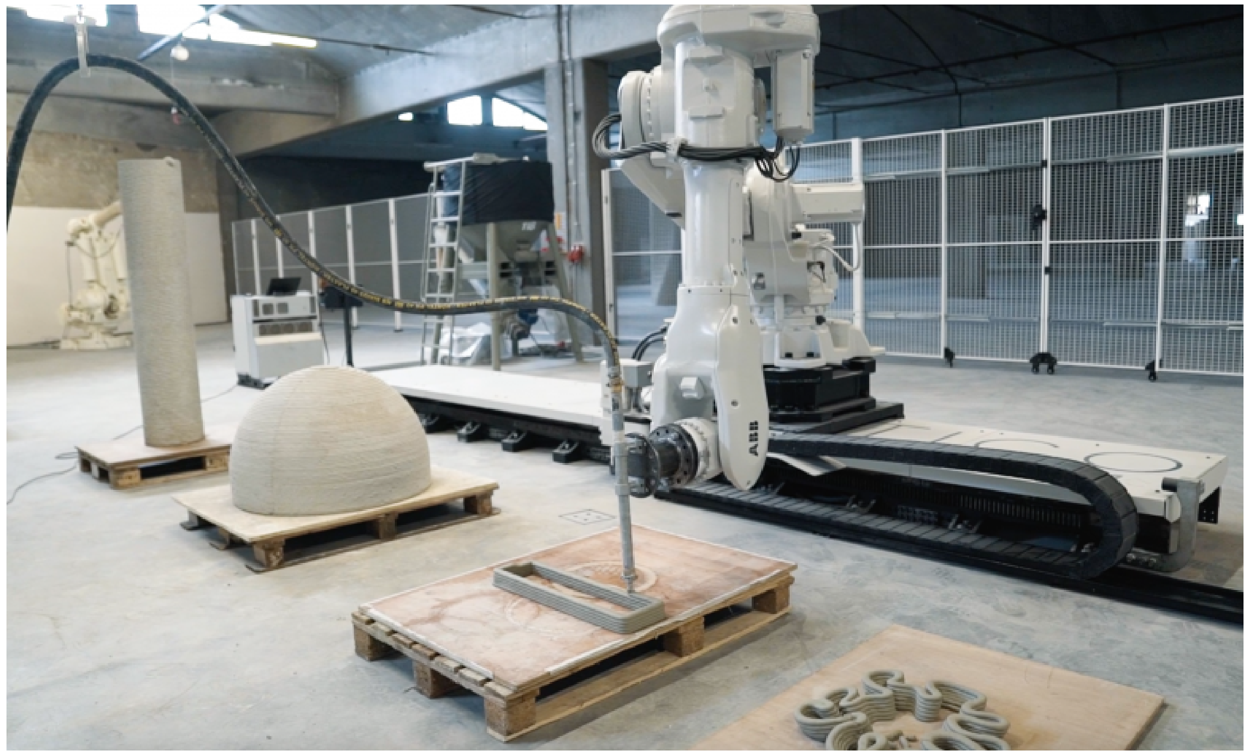


image / figure 2: 3D Printing with concrete

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The task will be to design a robotic builder that is able to use amorphous materials to build and use its own structures to expand their build area. Amorphous materials were chosen with the vision that the system could adapt to the different geometries of various environments. With such a fully autonomous and decentralized system, limitations can be found on the practical side of things. Creating a system that is able to build on its own while still being viable in its speed, reliability and capacity will be the challenge.
We seek to validate the performance of a single robot builder, that has the potential to be part of a larger team in the near future. Alas the control system will only be that of a singular builder, designing swarm strategy will be out of scope. Creating an integrated system is key to be able to validate this concept, therefore mainly off-the-shelf components must be used.
Research has already shown similar systems to be able to operate up to a certain degree[1]. We see additive manufacturing used dynamically and we see the system bridging gaps and height differences by building structures and using those said structures. Some limiting factors that should be covered are the capacity, material choice, locomotion strategy and integration in swarm tactics(local strategy must be designed with swarm tactics in mind).
The solution of this project can help lay the groundwork to integrate swarm robotics in the world of construction effectively providing a solution that can improve the industry.

[1] 1. A. J. Burns, "Material depositing mobile robots for application to cementitious additive manufacturing," 2020.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

This assignment will require the student to design and experimentally evaluate a mobile additive manufacturing robot capable of building three dimensional structures. The intention is for the robot to be able to climb the structure as it is being built. The focus will be on hardware integration at the systems level.

This project will require R&D in several categories; choices must be backed-up by prototypes and testing. A final prototype will be made that encapsulates all of the design choices into one integrated system. This prototype should help to further advance the concept of bio-inspired robotic swarm builders. Part of the research will also be published as a scientific paper.
This assignment can be divided in the following sections:
- Materials / Voxels
- Material deposition system
- Locomotion strategy
- Control system/strategy

We hope to us a system level integrated approach for this project, meaning that the novelty comes from integrating all of these sections into one system. In the first phase of the project conceptual design and literature review will be used to get an better understanding of each aspect. Several demonstration runs will be done before heading into the greenlight meeting(which will showcase the final demo). Before the mid-term evaluation a robust evaluation/demo of each project section will be shown(sections mentioned her above). After the Christmas break, the first integrated system will be shown in a demo.

Initials & Name LB Worang Student number 4393465

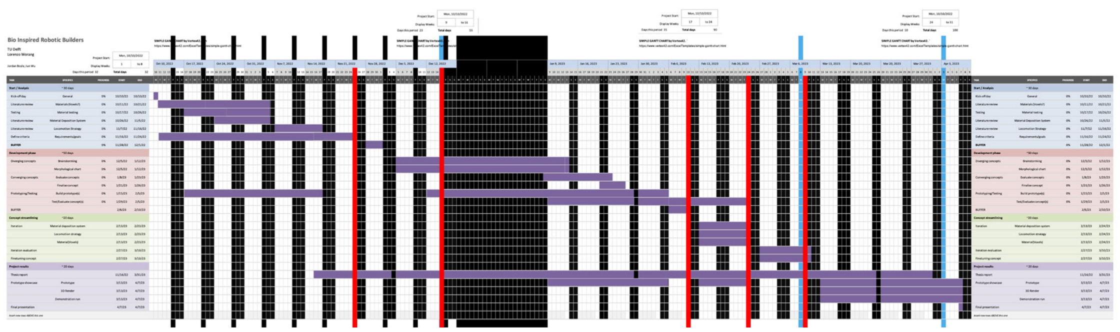
Title of Project Bio-inspired robotic builders

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 10 - 10 - 2022

6 - 4 - 2023 end date



- Black columns are day offs (incl. holidays and weekends)
- Blue columns are milestones (40 day, 80 day and 100 day mark)
- Red columns represent demo days (prototype milestones)
- First phase will be 4 day work weeks while the other phases have some 5 day work weeks.
- Above each period (8 weeks) you can find a small table with work days per specific period and cumulative workdays

Important for this project is to note that the first phase will be used for research by design by doing literature review parallel with conceptual design. After this phase a more converged plan of attack will be developed for the later phases. Designing novel systems for each section will not be realistic given the timespan. The knowledge gained in the first phase will be used to decide which sections can use established technology and which sections require more attention in the later phases, effectively reducing the scope in the process.
Mentor meetings should start off being bi-weekly and quickly turning into weekly meetings during the last part the analysis phase. Wherein Chair and Mentor meetings should be done at the end of every month.
I hope to go visit my family in Indonesia during Christmas, but there is a chance that will not go through. If not the 3 week period will be changed to a 2 week holiday.

Total weeks = 24
Midterm-evaluation: = 15-12-22, Greenlight= 08-03-23
Projected End date = 03-04-2023

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

Learning Ambitions

- Basic coding
- Dynamic robotics / Technical Design
- Integrated electronic systems
- Research by design
- Communication management

This project engulfs what I find interesting in product design, projects that doubles down in the integration part of IPD in which you have to combine various aspects and elements into one streamlined concept.

I want to use the early phases of this project to focus on my techniques to diverge. With a project like this thinking outside of the box can be very useful and I want to learn more about brainstorming techniques. I also want to deepen my knowledge in electronic systems and basic coding.

In the middle of the project I hope to converge using research by design. I am planning to iterate small design cycles using actual prototypes many times to hopefully converge into the most promising design concept.

In the final phase I hope to bring all my ideas together and focus on prototyping a builder with its own electronic system. Using codes to not only run the system but also try and validate it on larger scale by using simulations.

In all of my projects I have experienced a period where I go into what I call 'tunnel vision state' for a lack of better words. In this 'state' I tend to really hone in into a subject and work on it continuously until I figure the problem out. The focus and work rate is good, but I tend to trade in my communication skills for it. I tend to not discuss the subjects with my peers or mentors due to me not wanting them to see that I am in 'trouble' with something. It would mostly work out, but I'd argue that my results could have been a lot better if I took the time to openly discuss such matters and get input wherever I could. I hope to improve on my communication during this assignment, and use all the resources and bright minds that I have access to wisely.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.