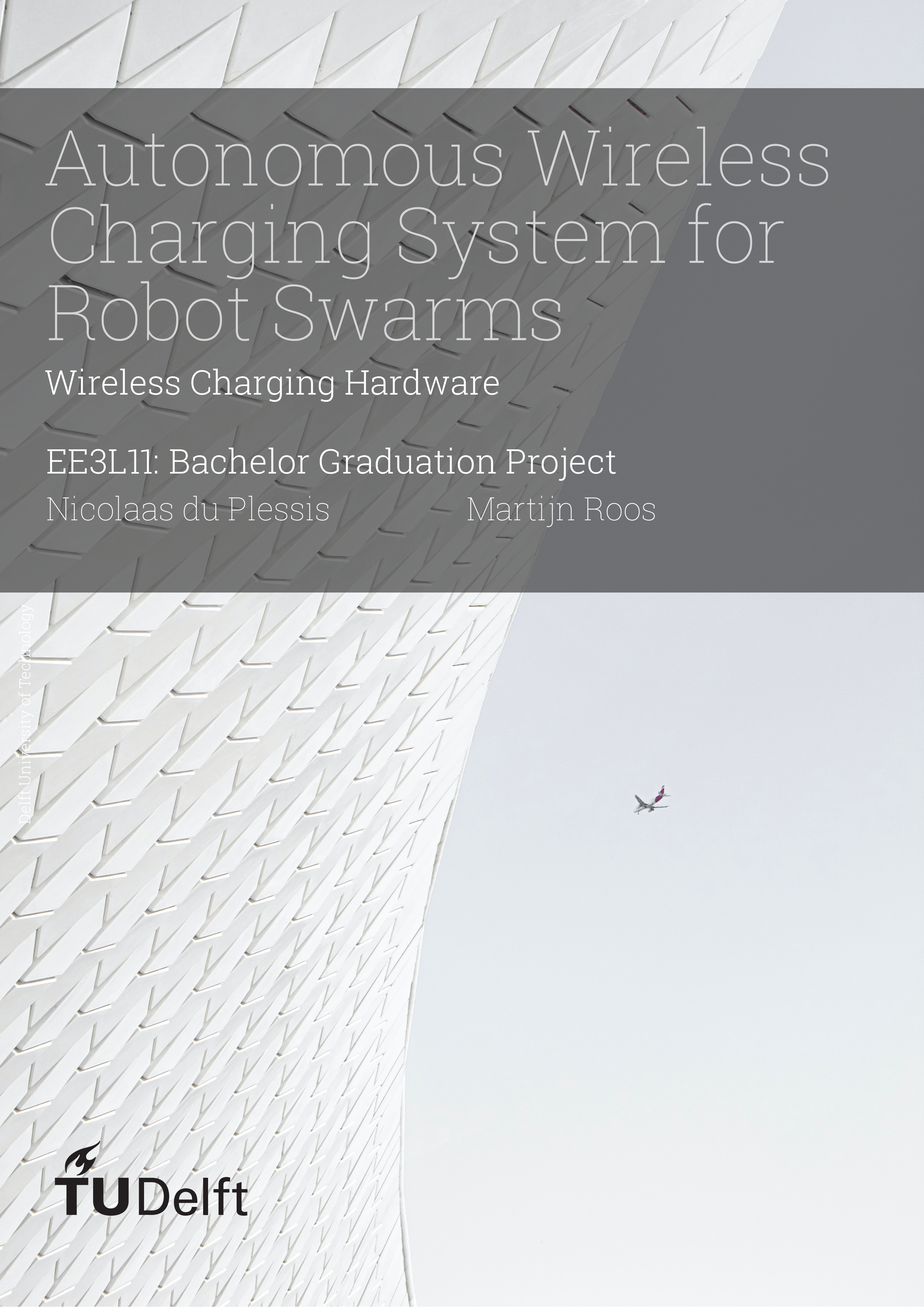

Autonomous Wireless Charging System for Robot Swarms

Wireless Charging Hardware

EE3L11: Bachelor Graduation Project

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Delft University of Technology

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by

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Abstract

This thesis aims to solve the problem of designing the hardware for a wireless charging system to be used for keeping an autonomous robot swarm alive. Previous designs available to us lacked essential safety features and were very specific in their application. Current wireless charging specifications are also not sufficient to cater to the needs of these systems. Using a detailed analysis and clear requirements, this thesis describes the process of developing the hardware for such a system with flexibility and safety in mind.

Preface

The next phase of Lunar exploration is expected to involve eventual deployment of autonomous robot swarms to fulfill a wide variety of missions. The TU Delft Lunar Zebro project is in the process of developing the first generation of these robots, and one of the challenges they face is the question of decentralized swarm recharging. This graduation project is aimed at investigating this question in context of an existing autonomous swarm development platform called "DuckieTown". Utilizing the platforms widespread accessibility to encourage further technological development and research of swarm recharging technology in the long term. The platform is also in the process of being deployed as an autonomous swarm demonstrator by the TU Delft Science Center for demonstration, education, and development purposes, further motivating the choice of focusing the investigation in this context.

The primary target audience is focused on technical roles including but not limited to designers, engineers, scientists, and managers, to provide them with a comprehensive overview of relevant requirements, and clear scientific justification for design choices in regards to the solutions.

We extend our gratitude to our supervisor ir.Dr. Chris Verhoeven, who apart from insisting on the unconventional order of his titles to highlight his conviction as an engineer, also offered his invaluable guidance and insights in regards to the technical challenges we aimed to investigate.

And finally, dear reader, thank you for taking the time to read our work, and we hope you enjoy our thesis as much as we enjoyed working on it!

Nicolaas du Plessis
Martijn Roos
Delft, June 2023

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Part I

Introduction & Requirements

1

Introduction

1.1. The Project

The goal of the project is to develop an autonomous charging solution for swarm robots as a basis for further development and improvements. The project can be divided in three subgroups as can be seen in Figure 1.1.

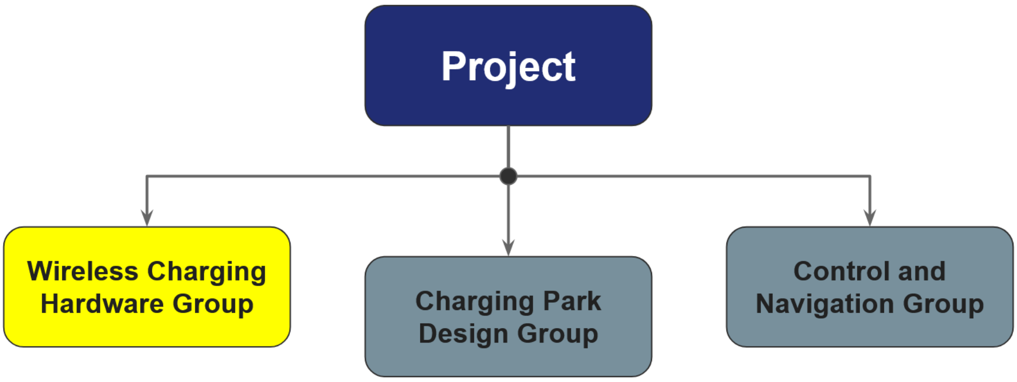

Figure 1.1: Overview of the project subgroups

1.2. General Overview

This thesis is focused on the hardware part of wireless charging for autonomous robot swarms. This is realized via a transmitter module located on a charging base station and a receiver module on a robot. A simple representation can be seen in Figure 1.2.

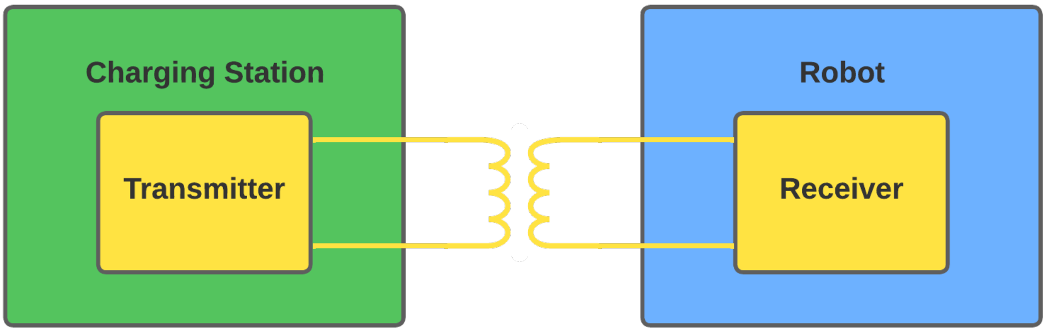

Figure 1.2: Simple overview of the system

1.3. Dependencies

As illustrated in Figure 1.1, the complete project is done in conjunction with a subgroup dedicated to control & navigation [1] and a subgroup dedicated to designing the charging station[2]. A high level overview of the dependencies between this thesis and the other subgroups can be seen in Figure 1.3. This thesis is focused on the power related parts, marked in yellow. A small part is related to software running on the robot marked in blue. As can be seen in Figure 1.3, one charging station can control multiple transmitters, therefore multiple robots can be charged in parallel. The charging station only requires power from one transmitter to operate.

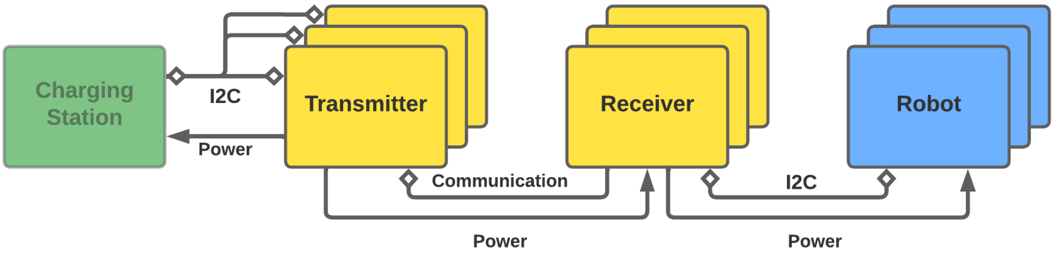

Figure 1.3: High level block diagram of the system

The charging station has the following dependencies:

- Receives power from the transmitter
- Sends commands to the transmitter
- Receives information about the robot from the transmitter

The control & navigation group has the following dependency:

- Sends SOC, PSOC and an Enable flag to the receiver.

Where SOC is the State Of Charge and PSOC is the Preferred State Of Charge. These variables are not required for the hardware part, but are passed along to the charging station. The receiver uses the enable flag. To relay the variables mentioned before, the transmitter and receiver can communicate unidirectional from the receiver to the transmitter.

1.4. Introducing the Duckiebot

The Duckiebot is a robot living in DuckieTown and is the proof of concept platform on which the system will be build. The Duckiebot is an open source platform used for educational purposes, mostly used to learn about robotics, AI and autonomy. The robot runs on the Robot Operating System (ROS [3]). This is an open source software that uses nodes that allow for all sorts of code in different languages to work with each other. The robot can be seen in Figure 1.4 alongside a DuckieTown in Figure 1.5.

Figure 1.4: A Duckiebot, credit: Duckie manual[4]

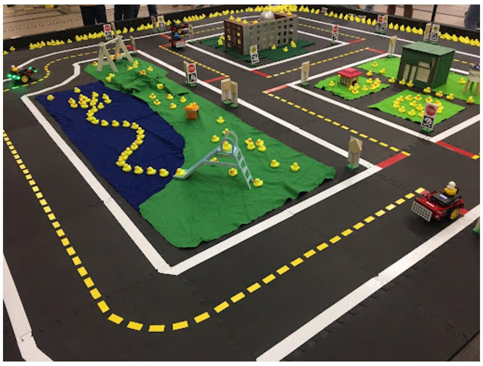

Figure 1.5: Example of a DuckieTown

1.5. Problem Definition

1.5.1. Situation Assessment

During the research of what had already been done, "Autonomous Recharging Of Mobile Robots" [5] along with "A Comprehensive Analysis of Wireless Charging Systems for Electric Vehicles" [6] gave us great information on where to start. Currently, the systems often not wireless and are often not fully autonomous but use centralized command. The systems are often also very specialized and are not scalable to other applications. The combination of these requirements is most likely under development with other parties, but is not yet publicly available. The goal therefore, is to develop a system that is both wireless and autonomous and scalable.

1.5.2. Scoping & Bounding

The system is intended to combine both already existing products & methods and improve upon them. Improvements are to be made in safety, autonomy and scalability.

2

Program of Requirements

The following sections give an overview of the requirements and a detailed breakdown of the refinement process for each. Requirements are classified into the following categories, along with identifiers to aid in referencing throughout the document.

MR Mandatory: Acceptance requirements that the product must fulfill, and tested with a discrete acceptance criteria (I.E. pass/fail).

TR Trade-Off: Requirements that the product should fulfill, and tested with a continuous acceptance criteria that can be within design trade-off decisions. (I.E. score).

FR Functional: Requirements that are inherent to either the scope of the product, or part of the agreed functional abstraction between sub-groups, as outlined in the introduction.

NR Non-Functional: Requirements that are important attributes to be considered in the design of the product

2.1. Mandatory Requirements

2.1.1. [MR1] Minimum Power Transfer

The product must achieve a minimum power transfer of 10W at the receiver output under well defined worst-case charging coil misalignment. The minimum power is based on the Duckiebot's battery which requires a 5V USB charger with up to 2A supply, as states in the manual [7]. The worst-case misalignment have been defined based on the physical dimensions on the Duckiebot as shown in Figure A.1 & Figure A.2 (which can be found in Appendix A) to be 24mm of radial misalignment (Using a 1 inch diameter coil) and 21mm of axial misalignment between the coils.

2.1.2. [MR2] Receiver Output Specifications

The receiver hardware must output the correct voltage at 5V as required by the Duckiebot's battery for charger (see [7]), as well as a continuous current drawn of up to 2A without the output voltage falling below the USB voltage specification of 4.75V (see [8]).

2.1.3. [MR3] Receiver Authentication

The product must have some form of receiver authentication for the transmitter to verify when the transmitter coil may be energized at higher voltages. This ensures that the transmitter coils flux density remains low enough to avoid damaging foreign devices that may experience induced currents, such as wireless charging receivers in portable electronics.

2.1.4. [MR4] Power Surges

The product must safely handle power surges that can occur during abrupt changes in the wireless coupling mechanism. Two specific situation in particular are, 1: when the receiver stops drawing power, causing a rapid change in the reflected impedance at the transmitter coil, and 2: when the transmitter coils magnetic field collapses (due to shunting of the transmitter coil), causing the receiver coils magnetic field to collapse as well.

2.1.5. [MR5] Detection of Coil Coupling Changes

The product must detect and handle changes in the magnetic coupling between the transmitter and receiver coils in a predetermined way. These changes can be attributed to a changing misalignment between the coils, as well as foreign objects being placed close to or between the coil pairs and influencing the coupling factor.

2.1.6. [MR6] Exposed Voltage Limitations

The product must ensure that no voltage above 75 V DC or 50 V AC is accessible at any point on the product. As the product is to be deployed in an educational, promotion, and research environment with limited access control within the EU, the product must comply with the European Union General Product Safety Directive (2001/95/EC [9]) for consumer goods. This requirement is stricter than the "Extra Low Voltage levels" interpretation by the IEC Basic Safety Publication (61140:2016 [10]), and can therefore be considered complaint internationally as well.

2.2. Trade-Off Requirements

2.2.1. [TR1] Real-time Power Transfer Optimization

The product should optimize the power transfer between the transmitter and receiver in real time to maximize efficiency, allowing for compensation of factors contributing to efficiency loss such as position misalignment, initial component parameter variance, and component parameter changes over time.

2.2.2. [TR2] Real-time Electromagnetic Interference Optimization

The product should minimize the stray magnetic field leakage in real time to avoid unnecessary coupling and interference with other systems, as the product is expected to be deployed in an array of multiple transmitters to form a charging station.

2.2.3. [TR3] Cost

The product should optimize the material and integration costs to a minimum. The receiver in particular is designed to be deployed on each individual robot within large swarm, results in high sensitivity of unit cost towards total system costs.

2.3. Functional Requirements

2.3.1. [FR1] Wireless Power Transfer

The product must use wireless power transfer as outlined by the context of the investigation as outlined in the introduction. The absence of electrical contacts for recharging allows for extended reliability and service life, and the wireless nature of the power transfer allows for hermetic isolation of the systems from the outside environment as well as relaxed tolerance in positional misalignment.

2.3.2. [FR2] Receiver -> Transmitter Communication

The product must accommodate a unidirectional data stream from the receiver to the transmitter to allow for transfer of robot parameters during charging to the charging station, as outlined in the introduction in Figure 1.3. The receivers ROS module must accept these parameters and ensure they are transferred to the transmitter, where they are made available to the charging station via a standard I2C bus (further details outline below in requirement 2.3.4. The minimum available bandwidth must be at least 160bits/s, grouped into packages of 4 bytes every 200ms [5Hz].

2.3.3. [FR3] Duckiebot Integration

The receiver must integrate with the onboard software of the Duckiebot, which runs Robot Operating System [3], an open-source widely adopted software framework. Furthermore, the hardware to be implemented must fit on the Duckiebot without restricting its movement.

2.3.4. [FR4] Charging Station Integration

The transmitter must integrate with the charging station as outlined in the introduction in figure REF. Communication takes the form of a standard I2C bus where the transmitter behaves as a slave device with configurable address, allowing multiple receivers to be incorporated into a single charging station. Power must be supplied from the transmitter to the charging station at 5V output up to 2A, with reverse current protection allowing multiple transmitters to parallel their power supplies for the charging station.

2.4. Non-Functional Requirements

2.4.1. [NR1] Reliability

The product should be designed to promote reliability of the electronics, especially in regards to extending operation lifetime, and realizing robust solutions through simple design approaches. Lifetime is specifically dictated by extended high-temperature operation and frequent heat cycles, which should be minimized to promote reliability.

2.4.2. [NR2] Efficiency

The product should consider efficiency in the topology and component selection, in particular in conduction paths where large currents are expected to flow (such as driving circuits). This requirement also complements the previous one in reducing operation temperatures through minimizing unnecessary losses.

2.4.3. [NR3] Interference

The product should minimize electromagnetic interference of the transmitter coil, in particular when not transferring power to the receiver. As multiple transmitters are expected to be used in a charging station, interference generated by the product may cause unexpected behaviour in surrounding devices.

2.4.4. [NR4] Serviceability

The product should maintain serviceability of the design through the use of standardized component packages and behaviours, so that easy changes and replacements can be made. This complements the target use case of being deployed in a development environment, where further development can be done on smaller sections of the design instead of changing the full product as a whole. To that end, the product should be insensitive to component changes, and make use of open-source development frameworks to implement solutions.

Part II

Design Process

3

Design analysis

3.1. Wireless Technology

The primary requirement is that the product must use wireless power transfer in order to transfer energy from the transmitter to the receiver (subsection 2.1.1). The analysis of the previous design as done in the introduction was based on rudimentary inductive charging, and while effective in its simplicity, had significant drawbacks on which many of the subsequent requirements were based. We can start with looking at the fundamentals of the technology.

3.1.1. Inductive Charging

Inductive charging works on the principle that two coils are coupled together to form a transformer, using the air as the transformer core. The the magnetic flux produced by the changing current in the transmitter coil induces a current in the receiver coil based on the coupling factor between the coils. In practice this means that to achieve the most power transfer you want the tightest coupling between the coils, meaning that you want to maximize the magnetic flux captured by the receiver coil, as illustrated below in Figure 3.1.

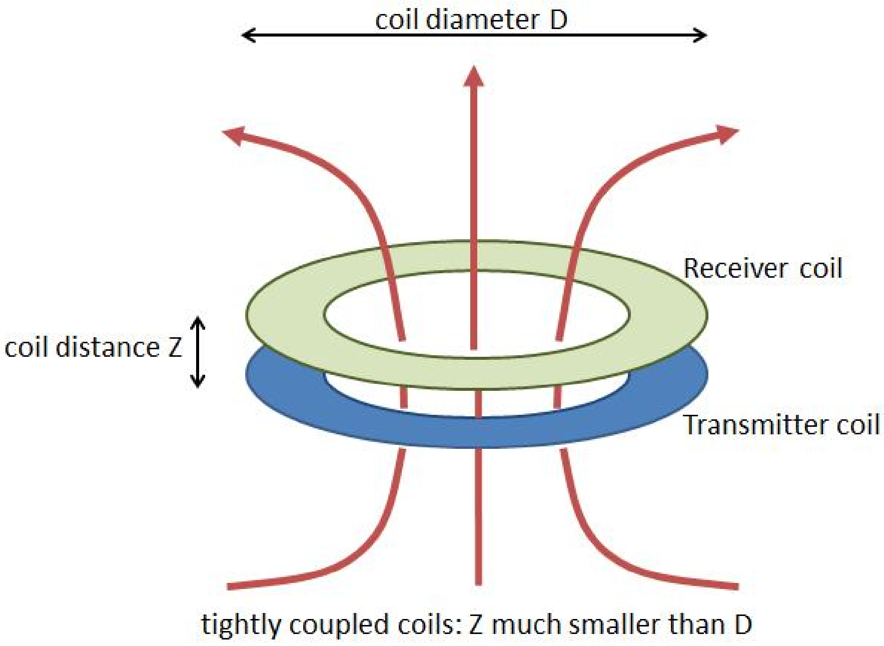

Figure 3.1: Credit: Wireless Power Consortium [11]

This magnetic coupling is described as the coupling factor k, and can be expressed as follows $k = \frac{M}{sqrt L_1 L_2}$, where M is the the mutual inductance of the coils, and L_1 and L_2 are the self inductance of each separate coil. Furthermore, the power transfer is also dictated by the relationship between the resistance R and inductance L of the coils, and is quantified by the Q factor $Q = \frac{2\pi \cdot f \cdot L}{R}$, where f is the frequency. This indicates that power transfer can be maximized by using coils with a high Q factor, and as higher frequencies also increase eddy current losses within the coils, a high Q factor is required at a lowest possible frequency. Given that these coils parameters are geometrically fixed, many off-the-shelf coils are available that optimize the size, power transfer, and high Q factor of coils for these applications.

All that is left is to drive the tightly coupled coils with alternating current at the transmitter, and rectify the output and the receiver, and we have achieved wireless inductive charging, as shown in the circuit below in Figure 3.2. While the coils could be driven with a voltage square wave, the resulting current waveform would results in a triangle waveform with significant harmonic content, which is not ideal for efficient power transfer. As such, a sinusoidal drive would be ideal.

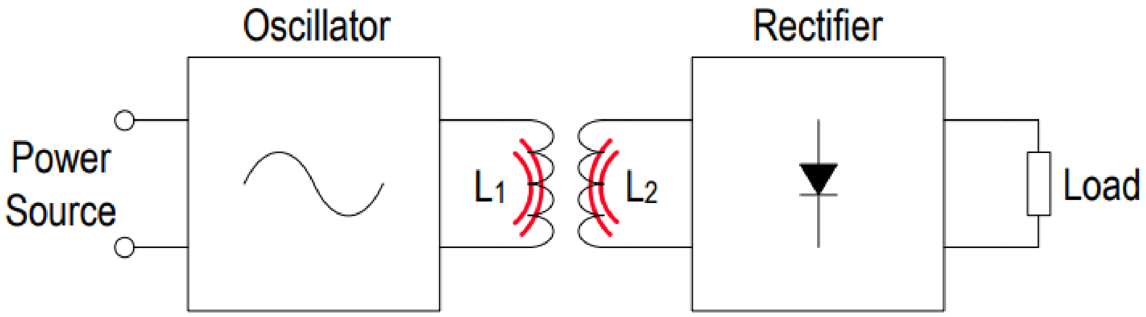

Figure 3.2: Credit: Würth Elektronic [12]

3.1.2. Inductive Charging with Resonant Tanks

In order to generate a sinusoidal excitation signal for the transmitter coil, the most common circuit implementation is a resonant tank, as illustrated below in Figure 3.3.

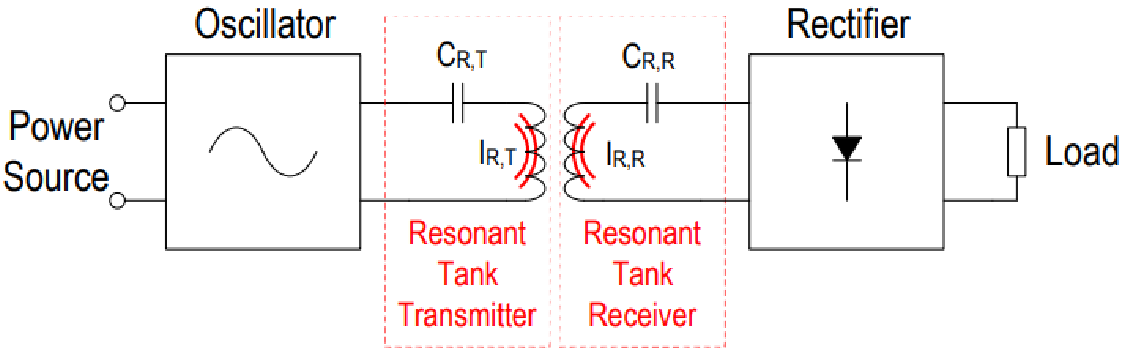

Figure 3.3: Credit: Würth Elektronic [12]

The addition of a series capacitor with the coil results in a series resonant LC circuit that can generate a smooth sinusoidal waveform. As this LC circuit needs to resonate as the same frequency as the peak Q factor of the coupled coils, the peak Q factor frequency of the LC circuit (the resonant frequency) would need to match those of the coils, and so the capacitor value is chosen accordingly. The choice of capacitor is also important, as the series resistance adds dampening and thus reduces the LC circuit's Q factor, resulting in ceramic of film capacitor being used in this application. The same capacitor value is chosen for receiver circuit as well, to keep the two circuit matched.

This concept works well in theory, but in practice components are never matched well enough to achieve the highest Q factor at the same frequency for both the coupled coils and the resonant tanks. Furthermore, the moment we change the coupling factor of the two coils, of use different coils for both receiver and transmitter, the ideal operational frequency of the two coils are no longer the same, and the optimum drive frequency of the circuit would lie somewhere between the frequency of the two coils.

Lastly, the maximum possible power transfer drop off greatly as the coupling factor decreases, and has been shown in literature [13] to be as low as $k = 0.5$ when the distance between the coils approaches 3 times the coil diameter, assuming no other mis-alignment or variations. Indeed, using this method would results in very high losses based on the worst-case miss alignment as outlined in requirement 1.

3.1.3. Resonant Inductive Charging

An alternative solution is resonant inductive charging, where a capacitor is placed in parallel with the coils, resulting in parallel resonant LC tanks, as shown below in Figure 3.4.

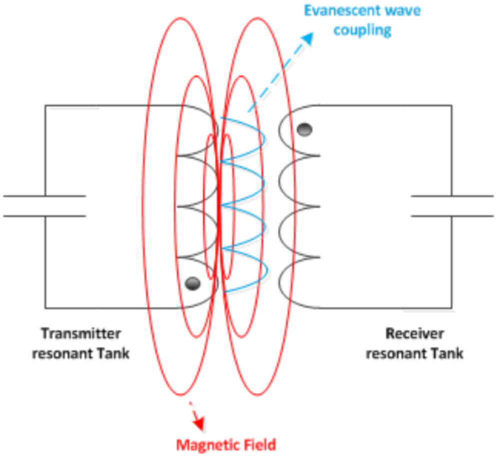

Figure 3.4: Credit: Würth Elektronic [14]

The advantage of this technique is that it can be used with loosely couple coils, as illustrated below in Figure 3.5.

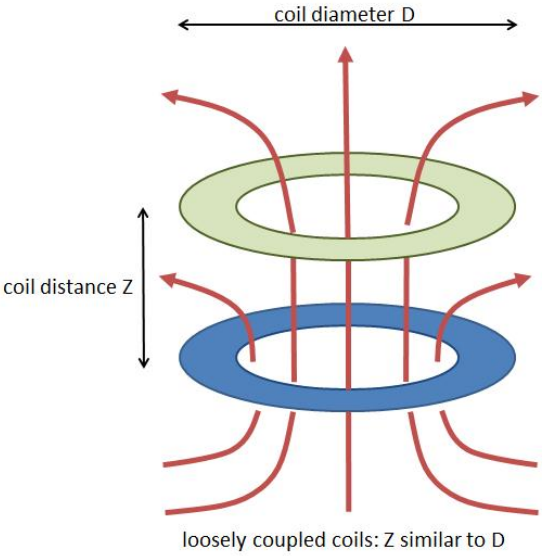

Figure 3.5: Credit: Wireless Power Consortium [11]

The resonance of the parallel capacitor on the transmitter cancels out effective contribution of the stray inductance of the transmitting coil, and the parallel capacitor on the receiver similarly resonances with the receiver coil such that the magnetising current of the receiving coil can be compensated. As such, resonant inductive charging has been shown to operate at much higher efficiencies for low coupling factors [15].

The disadvantage of this technique is much higher field leakage that results in increased electromagnetic radiation. However by driving the transmitter coil off it's resonant frequency, the resulting magnetic flux can be reduced, allowing control over the resulting EMI emissions as well as optimum power transfer by adjusting this frequency in real time. Furthermore, as the transmitter driving frequency is adjusted away from the parallel LC resonant frequency, the pair of coils transition to behaving as inductive charging coils once again, allowing for more efficiency wireless power transfer when the coil coupling is tighter.

3.1.4. Existing Standards

The Wireless Power Consortium [WPC] has already developed a standard for wireless power transfer called QI. The specifications of the standard [16] allows for operation in both Inductive and Resonant Inductive charging regimes, but currently are limited to power transfer level of 15W maximum. Furthermore, many manufacturers have only adopted this standard by implementing only inductive charging for consumer electronics, which suffers from very high sensitivity to mis-alignment, and would not be suitable for this application. Lastly, the specification requires highly specialized integrated IC's to negotiate and authentic between certified devices, which also increase the complexity of the product significantly.

The WPC is at the time of writing developing higher power standard called "Medium Power Wireless Charging" [17], but has yet to release specific of the standard, as it is currently in the draft stage and only accessible to constituting industry partners. As such, the choice was made to implement a simplified version of resonant inductive charging for the product.

3.2. Charging Speeds

The charging speed of the product has been stated in the requirements to be 15W subsection 2.1.1, but an investigation was done into overcoming this limit for practical reasons. As the batteries of Duckiebot robots have very large capacities, the slow charging speed would result in charging times in excess of 5 hours if the batteries are near empty. This was identified in the early stages as a potential flaw in the large scale deployment of a Duckietown autonomous swarm, as you would need to deploy a charging transmitter for very 2 robots in the swarm.

One solution that was investigated was designing a drop-in replacement for the Duckiebot battery that would have a different charge controller and LiFePO4 battery cell layout in order to allow for much faster charging. The biggest concern was that this would introduce a very hazardous change to the Duckiebot design that would not be compatible with the deployment environment of operating autonomously in a public space, and used for development and experimentation. Furthermore, after analysis of the legacy power transmitter design and the fundamental flaws it had, it was clear that scope of the project did not support the necessarity changed to the Duckiebot battery in order to facilitate faster charging speeds.

3.3. Swarm Deployment

The intended application for this system is to be used in swarms. That is, one transmitter on many receivers. Therefore the receiver should be simple and cheap to implement. Because of this, the choice was made to make the receiver 'dumb' by including just a GPIO expander rather than a micro controller.

To cater to different robots with different needs, the receiver is designed with flexibility in mind when it comes to power and voltage levels, as well as expandable functionality. This means the receiver should be able to handle lower as well as bigger loads and is able to adjust the output voltage over a certain range. Furthermore, the receiver should have the option to add additional sensors and features.

3.4. Transmitter Power control

Transmitter power control is one of the fundamental key improvements over the legacy transmitter design, and it realized by adjusting the driving frequency of the transmitters resonant inductive coil in real time. The implementation only requires the measurement of the transmitter bus voltage and current, and for the receiver to measure and report the voltage and current over the communication channel that will need to be established (see next section). By measuring and comparing the input and output power, the transmitter can continuously vary the switching frequency in order to two important requirements.

3.4.1. Power Transfer Control

Requirement subsection 2.1.2 states that the minimum transferred power to the receiver must be at least 15W, and while this can be realized by operating the transmitter at the higher power possible at all times, this is counter productive to the efficiency and EMI requirements. As such, the reported receiver output power can be used by the transmitter to adjust the frequency to ensure that enough power is transferred.

3.4.2. Efficiency and EMI Control

The requirements subsection 2.2.2 and subsection 2.2.1 can be realized by adjusting the operational frequency based on the power balance in order to achieve the minimum input power required to achieve the required output power. This allows the optimum efficiency point to be found, and at the same time also results in the lowest achievable amount of magnetic flux leakage between the coupled coils for a given coupling factor.

3.5. Communication

In order to have a safe and efficient operation of the device, some form of communication is required. The device should only be active when a compatible receiver is present in order to avoid energizing the transmitter with the potential for the magnetic flux to couple to unintended electronic devices and cause damage. Once communication is established, sudden changes in power transfer also acts as a method of foreign object detection.

While this communication can be achieved by modulating the resonant frequency of the receiver coil by using additional switched capacitors (also called Q factor modulation), this method requires more complex methods of demodulation by the transmitter, and requires the transmitter to have already energized before authentication can be achieved.

A simpler alternative was chosen by using a IR transmitter LED along with a IR photo-detector to achieve unidirectional data transfer, along with standardized IR protocols that use ASK modulation at 38kHz to improve noise rejection and specificity of the transferred signal. Using 4 periods per bit, this yields a theoretical bit rate of $\frac{38kHz}{4} = 9500$ bits per second. This can subsequently be used to transmit voltage, current and additional data as per the requirement subsection 2.3.2, such as the State Of Charge (SOC) of the robot.

4

System integration

4.1. Transmitter-Charging Station Integration

The transmitters integration's with the charging station is simple as per the requirements. The transmitter needs to operate as an I2C slave, with slave addresses selection per device in order to facilitate multiple transmitters to be deployed together in a charging station. The charging station can adress control and data registers as per the I2C standard in order to control the transmitter, and read the data available from the transmitter, receiver, and the dedicated data stream from the robot as per requirement subsection 2.3.2

The transmitter also has a power input that is used to drive the wireless charging coils. In order to adhere to requirement subsection 2.1.6, the input voltage of the transmitter was chosen at 20-28V DC. The reason for this was to allow for a wide range of compatible power source to interface with the transmitter, and to ensure flexibility in power distribution for eventual deployment. The voltage range incorporates the standard 24V DC ±10% industrial bus voltage, as well as the standard 28V DC aerospace bus voltage. Furthermore, the input is them also compatible with USB-C Power Deliver (PD) profiles that output 20V DC, but this would require an external controller to ensure negotiation in compliance with the USB-C PD specification.

4.2. Receiver-Robot Integration

As stated before, the receiver uses a GPIO expander to facilitate the sensors and control outputs. This means that all decision making happens on the robot itself. To achieve this, a connection has to be made between the robot and receiver. This is done via an I2C bus, this solution was chosen for it being widely adopted and its simple connection method only requiring two wires.

On the robot itself, a ROS package sends the commands to the receiver. This leverages the already present processing power of the robot. This does have as a drawback that the polling rate of sensors will be slower, that is however no problem as the receiver is not very time sensitive and the sensors only need to be read a few times per second. Being implemented directly in the robot's main control system, it allows for a direct link between the robot's decisions and them being acted upon by the receiver, as the receiver now acts an extension of the robot rather than a standalone device. This ensures there are no conflicts between the commands of the robot and the receiver listening to them, as the receiver does not send request or commands to the robot.

Part III

Prototype Implementation & Validation

5

Transmitter implementation

5.1. Overview

The transmitter implementation features a microcontroller, a H-Bridge driving the transmitter coil (split into two Half-bridge units), Gate Drivers, and some power and sensing elements. Figure 6.1 gives a overview of the layout.

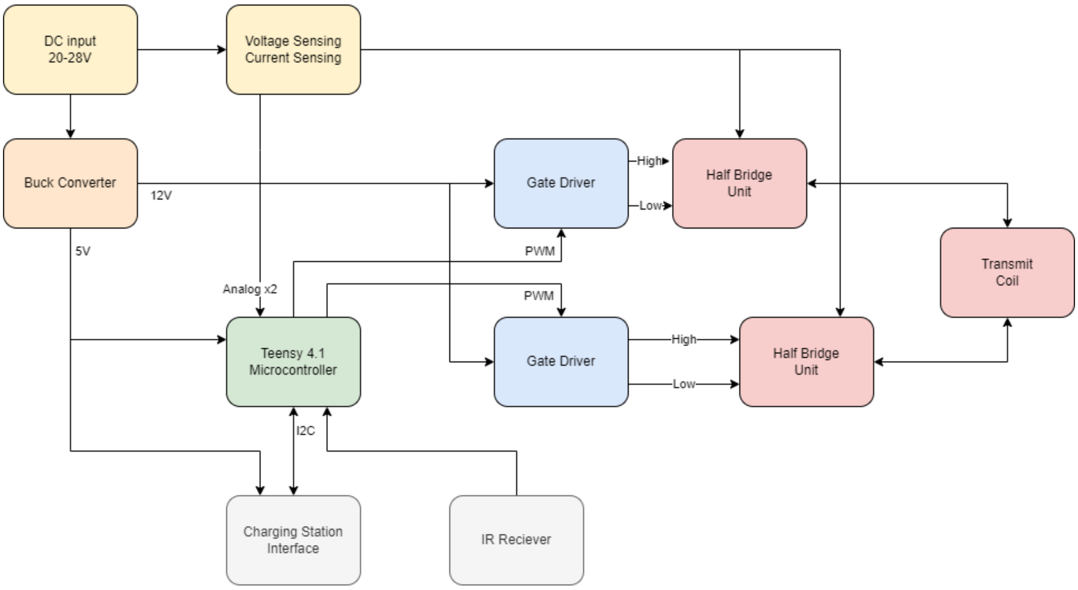

Figure 5.1: Block diagram of the transmitter

5.2. Half Bridge Units

While the implementation of the transmitter is mostly insensitive to design choices, the key focus of the design is understand the limitations of the simplified theoretical approach. While two half bridge driving a load seems like a simple implementation, the simplification of looking at the MOSFETS as simple switches can cause significant issues with excessive current and voltage oscillations that can easily destroy the MOSFETS and attached gate drivers.

The critical elements are highlight below in figure Figure 5.2, of which two specific elements should be focused on in particular. Firstly, the stray inductance L_{PCB}, L_{S_2}, and L_{d_1} should be kept to a minimum by placing the MOSFETS very close together with wide connections, as well as keep the distance to the DC bus capacitor C_{in} to the MOSFETS to a minimum. This avoids voltage overshoots over the mosfets during switching, and can prevent ringing at faster switching times.

Furthermore, the gate resistors R_{g_1} and R_{g_2} must be placed as close to the MOSFETS as possible, and the connection to the gate driver should be kept as short as possible as well. Excessive inductance on the gate will cause ringing between the parasitic inductance and internal capacitance of the MOSFET, cause the gate voltage to oscillate during a stitching transition, and potentially causing excessive losses or even shoot through (conduction of the DC bus through both Mosfets at the same time). The value for the gate resistor should be increase to lower the turn-on and turn-off currents, and slow the turn-on and turn-off transitions time of the MOSFETS.

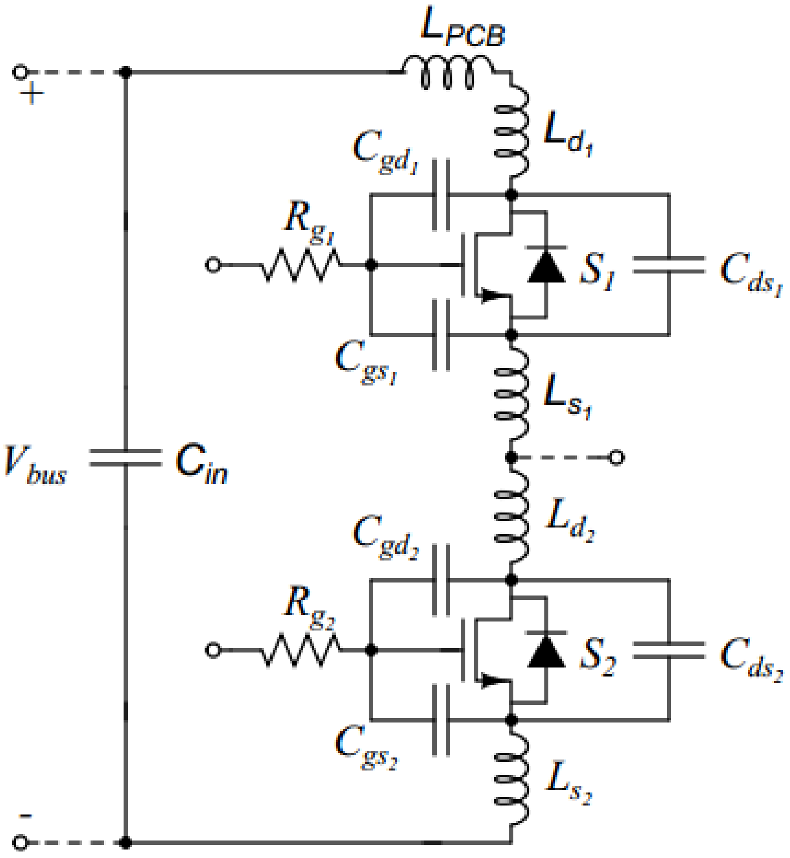

Figure 5.2: A half bridge driver highlighting critical stray elements [18]

5.3. PCB

Following this design, a PCB was designed and produced. This PCB can be seen in Figure 5.3

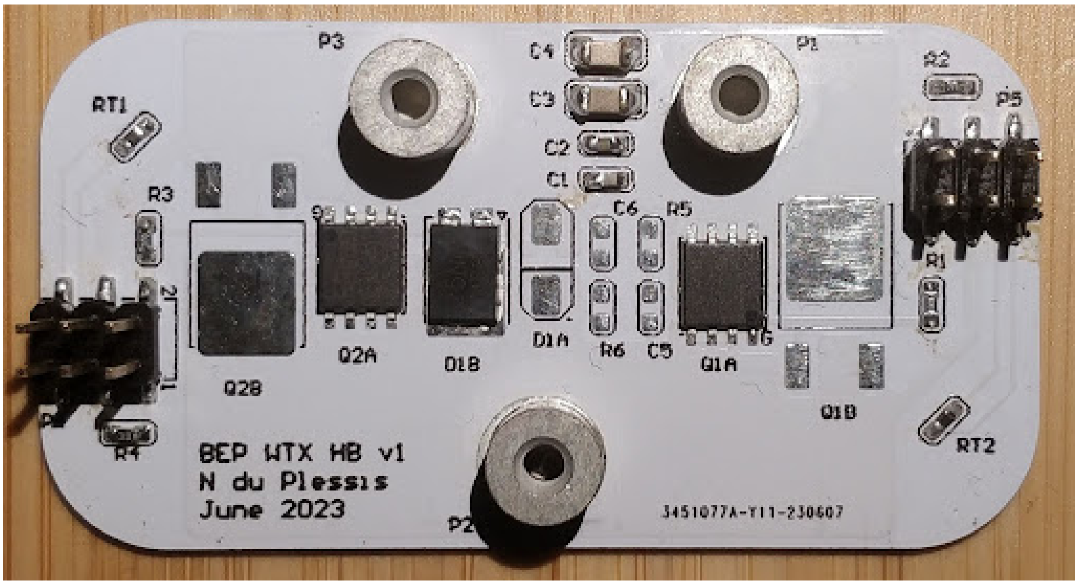

Figure 5.3: Transmitter PCB

6

Receiver implementation

6.1. Overview

The receiver can be divided in two distinct parts, namely, power and logic. The power circuit is responsible for transforming the incoming ac voltage to a stable (lower) dc voltage. The logic circuit is responsible for managing the communication between the robot and the receiver, such that the robot knows what voltage and current is present and can control when to start and stop charging. Furthermore it manages the communication between the robot and the transmitter. Figure 6.1 gives an overview of the receiver layout. Modules in yellow represent the power path, grey logic parts and blue is the robot itself.

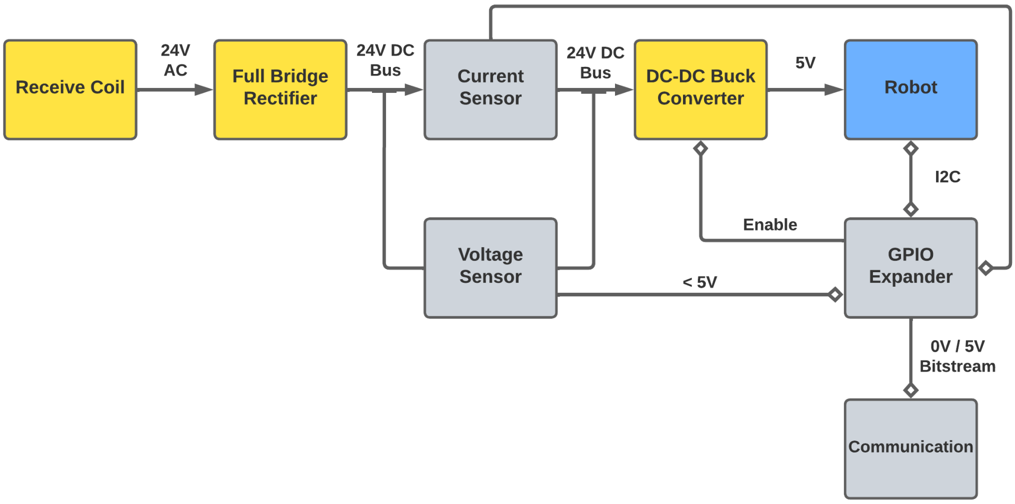

Figure 6.1: Block diagram of the receiver

6.2. Power

6.2.1. Resonance

In order to allow for resonant wireless charging, capacitors are placed after the coil. The value of these capacitors will be determined during the assembly time in order to compensate for different coils.

6.2.2. Rectification

To convert the incoming ac voltage to a dc voltage. A full bridge rectifier is used. For this rectifier, Schottky diodes were selected. This was done because the incoming voltage is relatively low and their lower voltage drop and therefore more efficient operation is favourable. After the rectifier a bulk and decoupling capacitor is placed to create a stable voltage. The values of these capacitors were determined in conjunction with the data sheet of the subsequent buck converter. To account for any sudden power spikes, a unidirectional TVS diode was added as protection.

6.2.3. Buck Converter

The dc-dc buck converter implemented consists of the lm2596s [19] voltage regulator in conjunction with input and output capacitances, a feedback network and a current loop consisting of a diode and inductor. During the design of the buck converter, a high efficiency buck-boost converter [20] was considered. This implementation was not chosen as a more traditional buck converter was satisfactory for the requirements and not as complex. The regulator was chosen according to the following requirements:

- Must be able to handle an input voltage of 5V to 30V
- Must be able to output a voltage of 5V to 20V
- Must be able to be switched on or off
- Must be able to output 3A
- Should be greater than 80% efficient
- Should have a ripple voltage smaller than 50mV peak to peak
- Should have a ripple current smaller than 50mA peak to peak

Using the feedback network, the output voltage can be calculated using the following formula:

$$V_{Out} = V_{Ref} \cdot \left(1 + \frac{R_2}{R_1}\right) \tag{6.1}$$

For $V_{Ref} = 1{,}23\mathrm{V}$, $R_1 = 1\mathrm{k}\Omega$ and R_2 between 0Ω and $20k\Omega$ this yields a voltage range of:

$$1,23V < V_{Out} < 25,83V \tag{6.2}$$

This satisfies the requirements set for the output voltage.

To make sure the output only turns on when a stable and sufficiently high voltage is present, the circuit was designed in such a way that the buck converters enable pin is high by default. This results in the buck converter being off. To enable the output, the enable pin has to actively be pulled low.

6.3. Logic

6.3.1. GPIO Expander

The main logic component of the receiver is the GPIO expander. This device manages all the communication between the robot and the sensors & outputs of the receiver. It interfaces with the robot via an I2C bus and follows the commands of the robot. To accommodate the various sensors and outputs the AD5593R [21] was chosen. This device was chosen according to the following requirements:

- Must have at least 4 input/output ports
- Must operate via an I2C bus
- Should be able to operate on up to 5V
- Should have internal ADC's & DAC's
- Should have an internal reference for the aforementioned ADC's
- May have extra input/output ports for future expandability

6.3.2. Sensors

Voltage Sensor

In order for the system to be safe for other devices, the transmitter will start sending 5V after the initial communication has completed. This voltage is too low for the receiver to create a stable 5V output from. Therefore, the receiver needs to keep the buck converter disabled until a satisfactory voltage level is present on the input. To do this, the receiver first uses a voltage divider to make sure the voltage present is within range of the ADC of the GPIO expander. Then it can simply be sampled by the GPIO expander.

Current Sensor

To allow the transmitter to conduct Maximum Power Point Tracking (MPPT), the current needs to be known alongside the voltage. To do this the ACS712 [22] current sensor was used. The only requirements for this sensor were the capability of handling 5A of current and an output voltage between 0V to 5V.

6.3.3. Communication

For communication, the receiver makes use of a 555 timer IC [23] to drive an IR LED. To adjust for tolerance in components, the feedback network for the frequency of the timer includes a variable resistor. This gives a frequency according to the following formula:

$$f = \left(\frac{1.443}{(R1 + 2R_2) \cdot C_1} \right) \tag{6.3}$$

For $R_1 = 1k\Omega$, $C_1 = 1nF$ and R_2 ranging from $13k\Omega$ to $23k\Omega$ This yields a frequency range of:

$$30,7kHz < f < 49,7kHz \tag{6.4}$$

The duty cycle can be determined via the equation:

$$\frac{R_1 + R_2}{R_1 + 2 \cdot R_2} \tag{6.5}$$

For the range of R_2 this yields a duty cycle of approximately 51% to 52%

The 555 timer was used in such a way that the IR LED only starts transmitting when a signal is applied from the GPIO expander. That is, without a signal the IR led is off.

6.4. Software

6.4.1. Overview

The software of the receiver runs on the robot itself and consists of multiple ROS nodes. Figure 6.2 shows a high level block diagram of the ROS nodes.

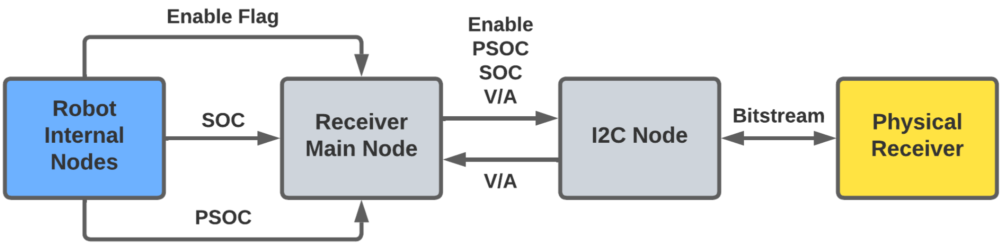

Figure 6.2: High level block diagram of the ROS nodes

6.4.2. Main Node

The main receiver node does most of the computing. It must perform the following tasks:

1. Ensure safe startup if charging is requested
2. Package all data to be send to the transmitter together
3. Disable the buck converter if a request to stop charging is made

6.4.3. I2C Node

The I2C node is responsible for the communication with the GPIO expander. It must perform the following task:

1. Initialize the GPIO expander when the system is started

2. Transform the packages from the main node into an I2C bitstream
3. Extract the relevant data from the messages of the GPIO expander and send these to the main node

6.5. Prototype

6.5.1. Constraints

Space on the duckiebot is limited, the best location for this prototype is on top of the duckie. Without restricting the exhaust fan or screen, this yields an usable area of 80mm x 80mm. To make the most of this area a PCB was designed. Mostly through hole components were selected due to them being easier to assemble and as to have a backup available in the form of a perfboard, might the pcb's not work or arrive in time.

6.5.2. PCB

The PCB was designed using the recommendations given in the datasheets of the key components (Voltage Regulator [19], GPIO Expander [21], Current Sensor [22] & 555 Timer IC [23]) and it was designed such that the power and logic components were separated as much as possible. A 3D render (Figure B.1), the schematic (Figure B.2) and the routing of the pcb (Figure B.3) can be found in Appendix B.

Following this design, a PCB was produced. Due to delays in component delivery however, the PCB could only party be populated. This PCB can be seen in Figure 6.3.

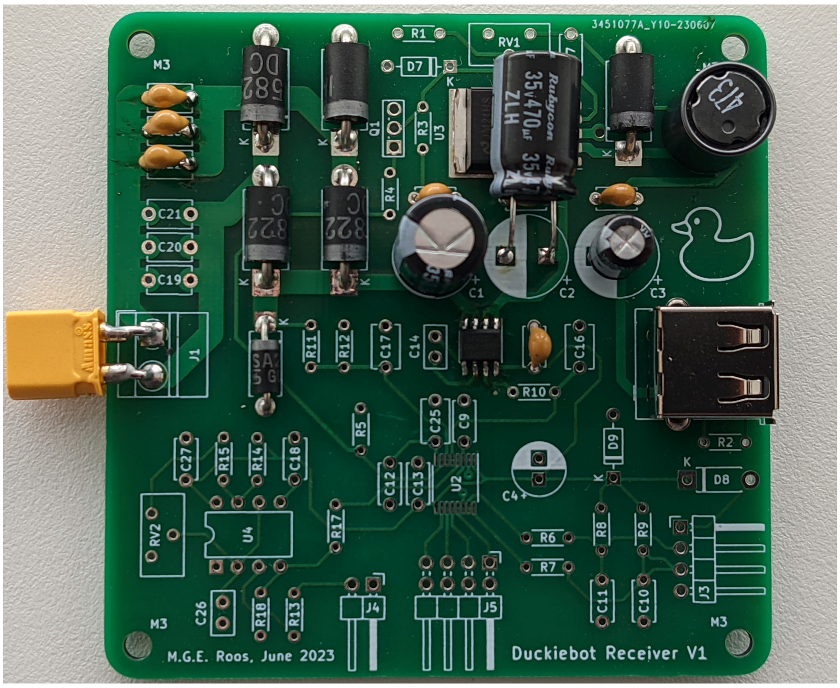

Figure 6.3: Receiver PCB

6.5.3. Casing

To further improve the safety of the device, it will be enclosed in a case such that nobody can accidentally touch the circuit.

6.6. Simulation

In order to validate if the design could work once produced and would pass the set requirements, a model of the power circuit and communication logic was made and simulated in LTspice. The simulations show behaviour as expected. Both the voltage and current ripple are within the requirements. The schematics & simulations for the power circuit (Figure C.1 & Figure C.2) and communication logic (Figure C.3 & Figure C.4) can be found in Appendix C.

Part IV

Discussion & Conclusion

7

Discussion

The requirements and design process for the product have highlighted the fundamental design decision that form the basis for a effective solution to the problems encountered.

While the requirement have set up with specific aspect of the design in mind, there are inevitable trade-off in the choices that have been made. The first of such is the limitation on scope that has results in having to incorporate the limitation of the Duckiebot's battery charging speed into the requirements. While the platform is mostly acceptable for the goal of deploying a development and demonstration focused autonomous robot swarm, the limitation in charging speeds will remain a fundamental hurdle in deploying large numbers to operate independently in a swarm.

Furthermore, one limitation of the wireless charging solution is the requirement for authentication before the transmitter is energized, as this has the inherent requirement that the robot must also be powered and enabled before charging can occur. While it is reasonable to expect that a fully depleted powered off robot will not autonomously find it's way onto a charge pad anymore, the limitation does mean that the technology cannot be scaled easily to provide remote or bi-directional recharging of robots with each other.

Lastly, the question of providing a convenient power source for the transmitters of a charging station have not been explored, in part due to the usage of a bench power supply for testing the prototype, as well as the limited testing environment that currently only had a single operational Duckiebot.

8

Conclusion

The main finding presented in this design analysis were focused on the following key improvement aspects over previous work down.

The choice of wireless power transfer technology was made to use resonant inductive power transfer in order to achieve the required power transfer under the alignment and separation conditions. This choice also allows future work to scale delivered power to higher levels while building on the same technology, albeit on a slightly larger scale.

Furthermore the inclusion of authentication and power reporting has been a key improvement over previous work where transmitters had no feedback in regards to transfer efficiency, as the real-time adjustments to achieve the required power transfer while maximising efficiency has made the system more forgiving of component and environmental variations.

Lastly, the implementation of the receiving hardware integrated onto the Duckiebot has the potential for significant future applications with the clearly shown merits in terms of the simplicity and easy of integration.

Part V

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Part VI

Appendix

A

Duckiebot Dimensions

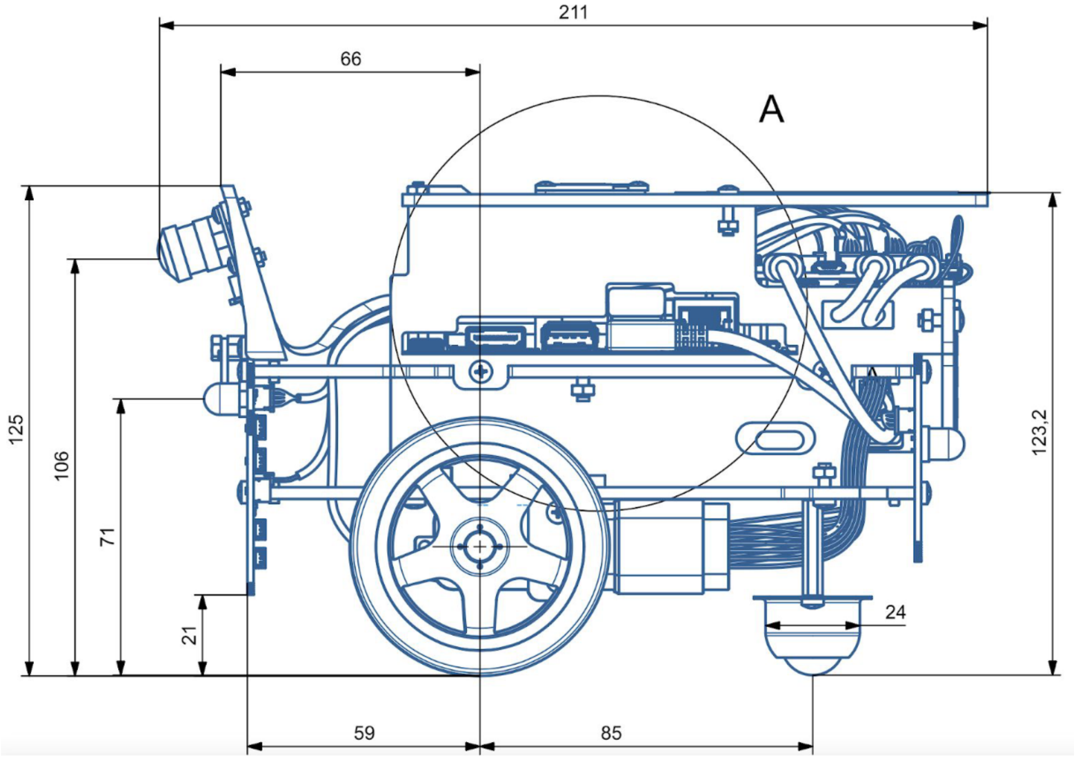

Figure A.1: Sideview of the Duckiebot, credit: Duckie manual[4]

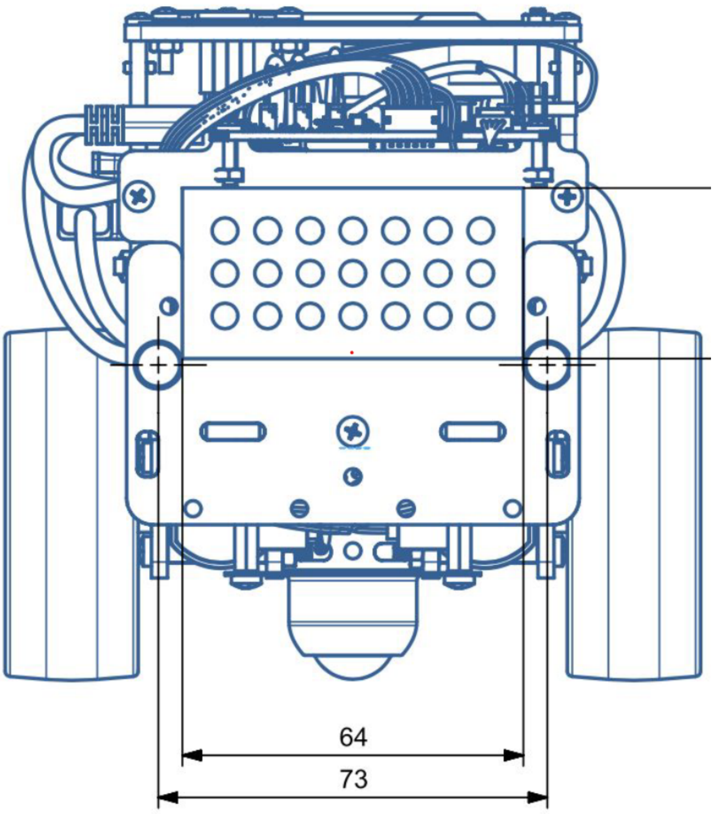

Figure A.2: Rearview of the Duckiebot, credit: Duckie manual[4]

B

Receiver PCB

B.1. 3D Render

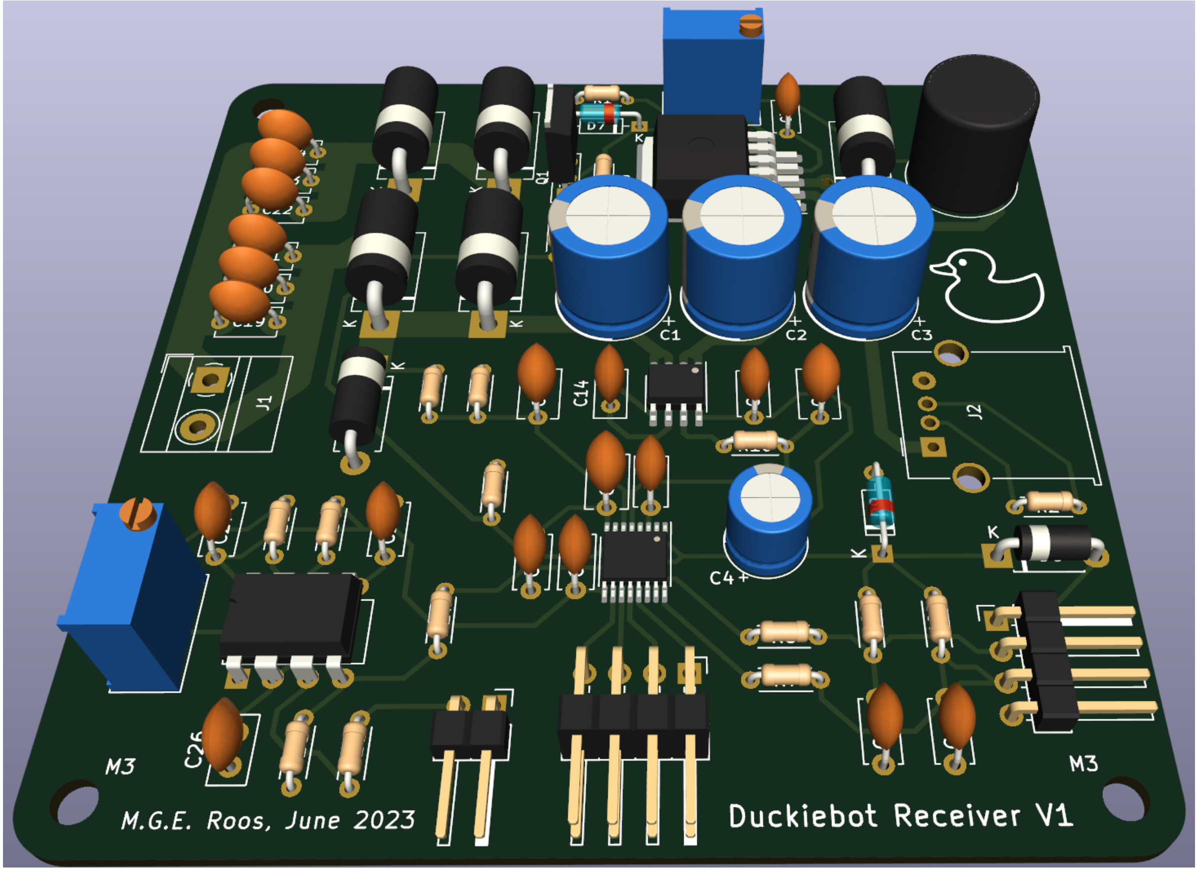

Figure B.1: 3D render of the receiver

B.2. Schematic

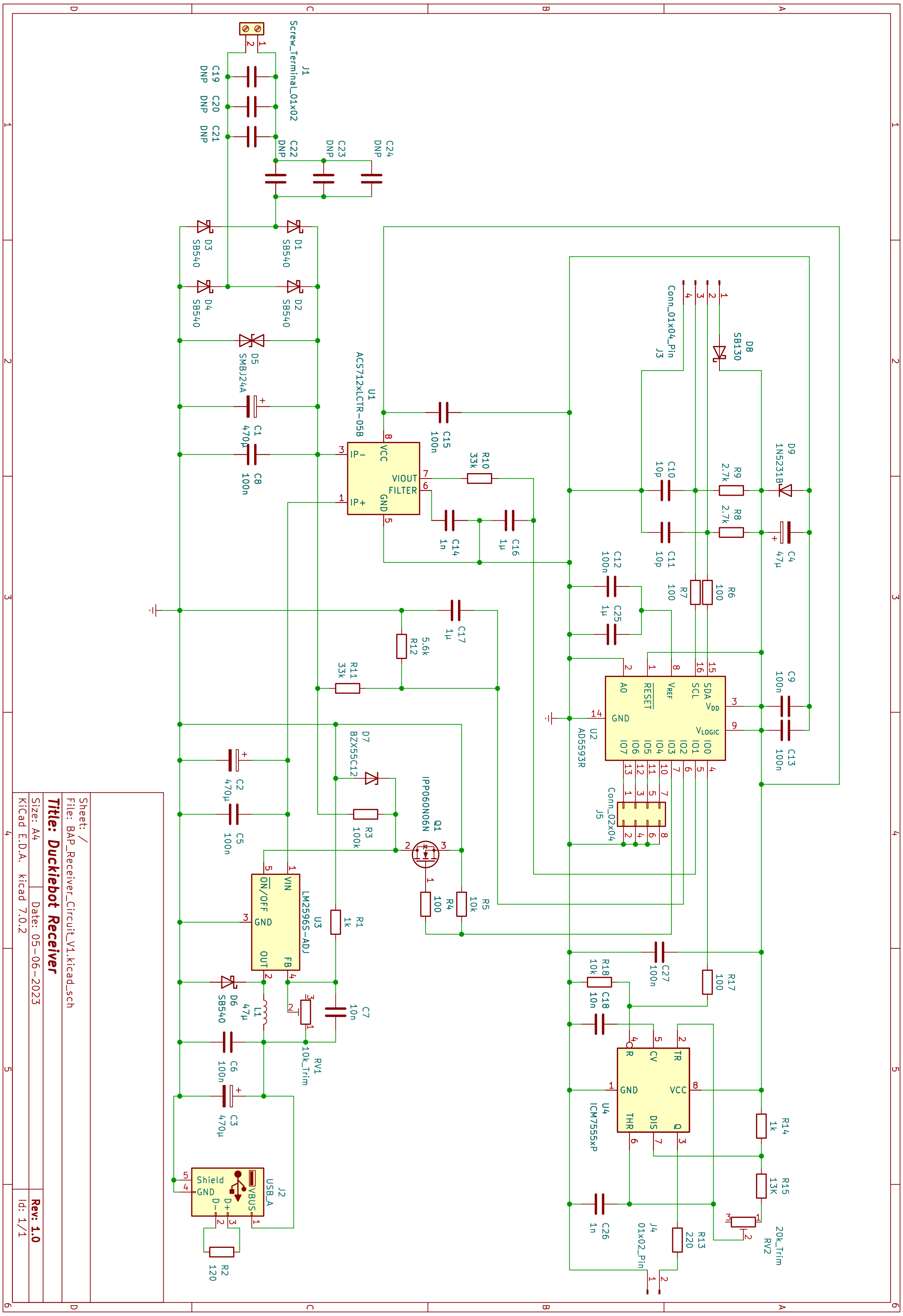

Figure B.2: Schematic for the receiver

B.3. PCB Routing

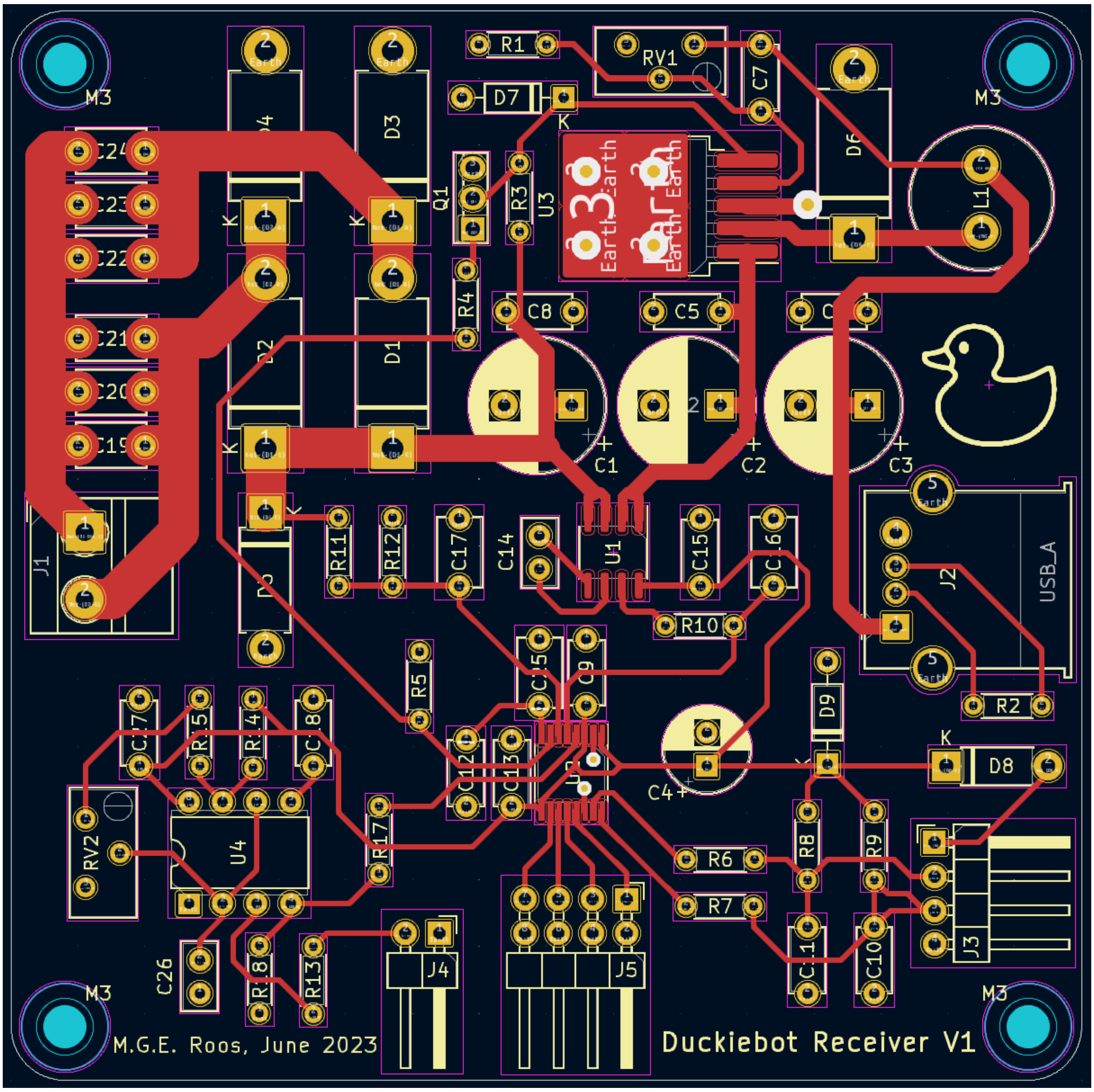

Figure B.3: PCB routing for the receiver

C

Receiver Simulation

C.1. Power Circuit

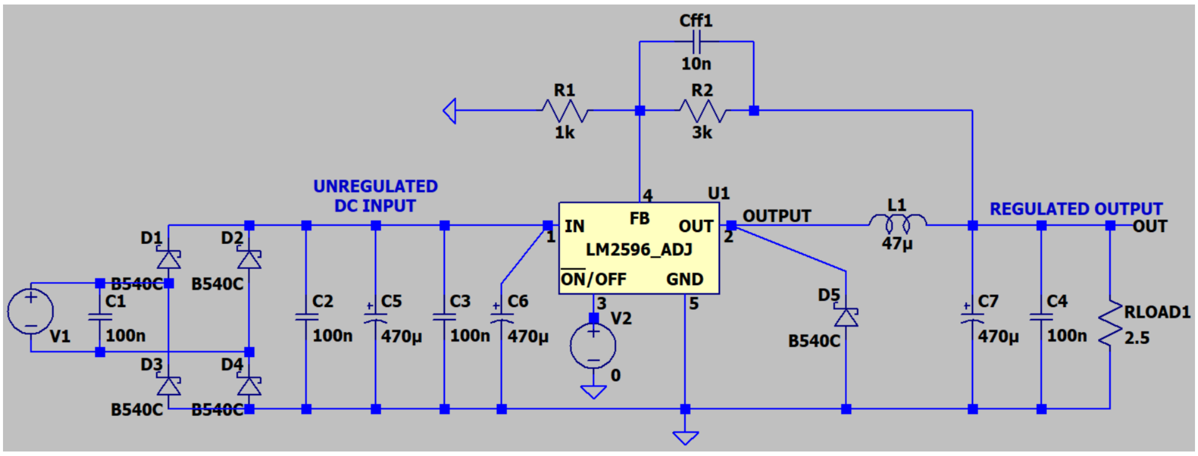

Figure C.1: LTSpice schematic of the power circuit

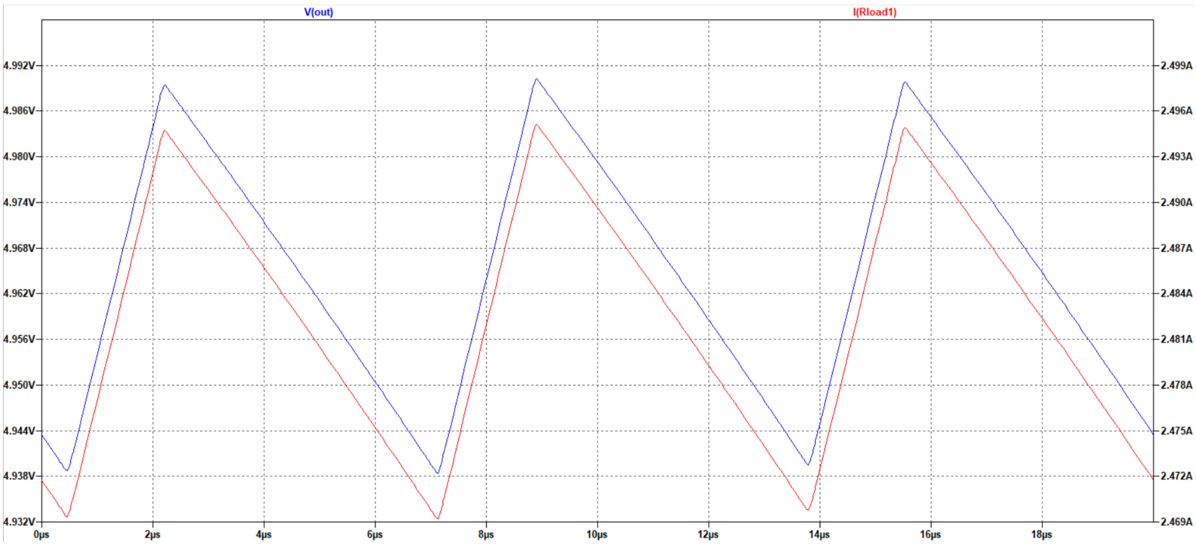

Figure C.2: Simulation of the steady state output of the receiver

C.2. Communication Logic

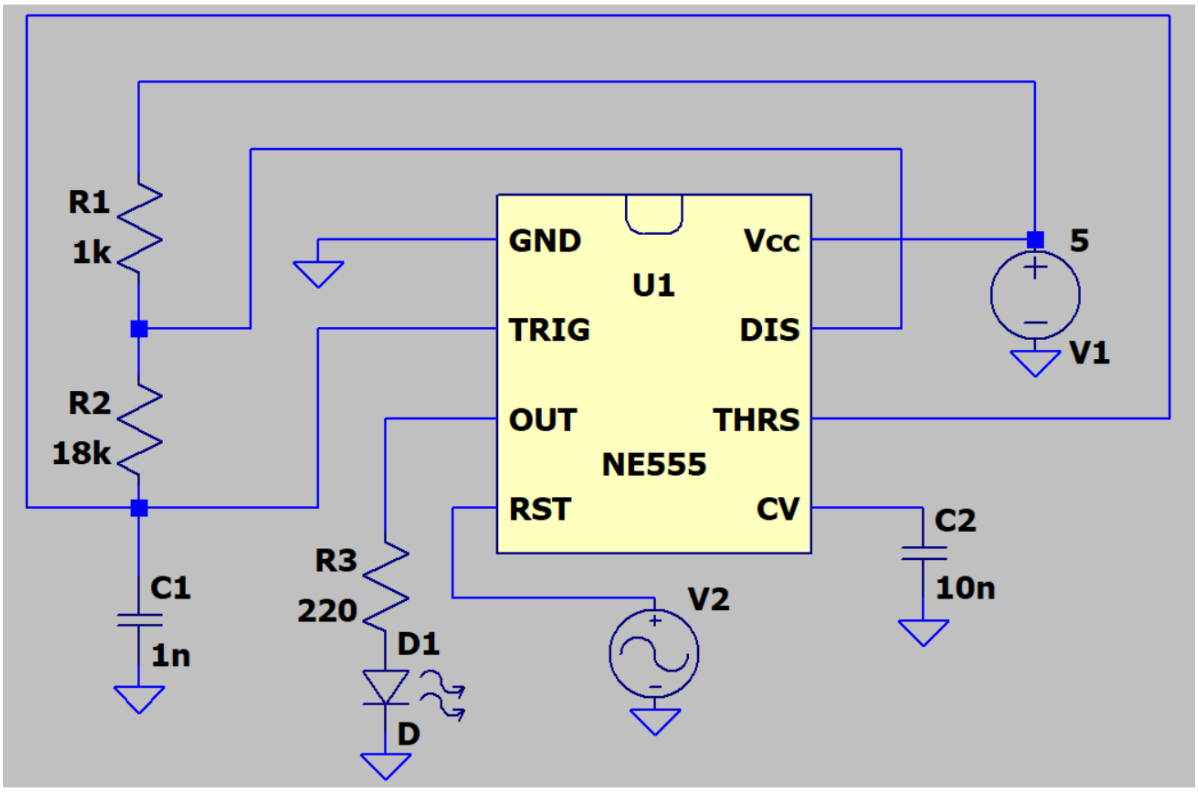

Figure C.3: LTSpice schematic of the communication logic

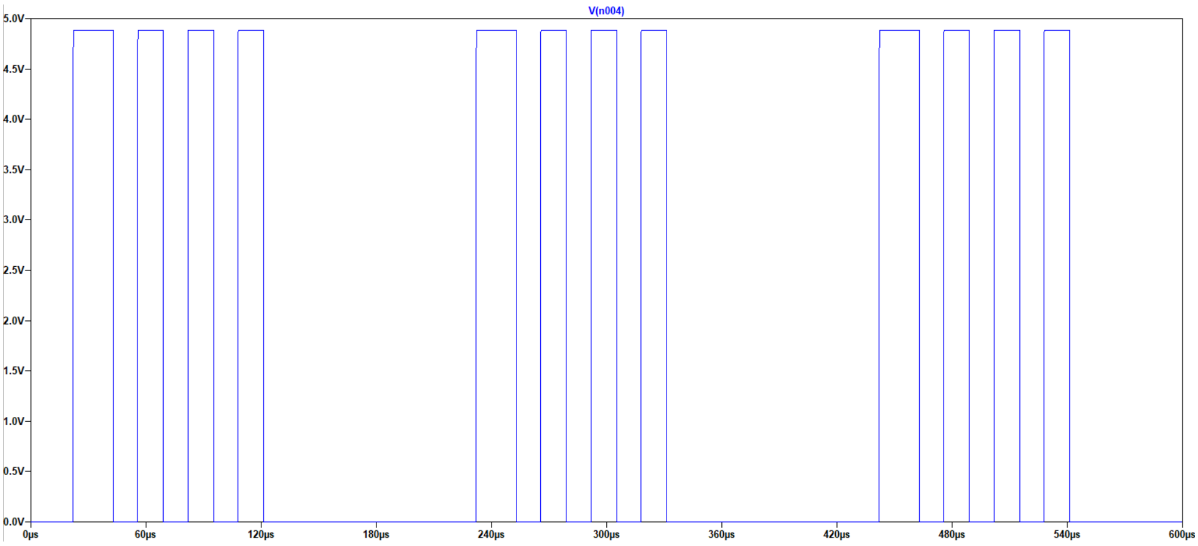

Figure C.4: Simulation of sending a 101010 bitstream