Development of an Electric Interface and a Cart-Docking Add-On for the mobile Assistance Robot Lio

Bachelor's Thesis 2024

Author:	Yan Gridling
Contact:	yan.gridling@stud.fhgr.ch
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Zusammenfassung / Management Summary

Diese Bachelorarbeit wurde in Zusammenarbeit mit der Firma F&P Personal Robotics erstellt. F&P ist im Bereich der kollaborativen Robotik tätig. Einer dieser Roboter ist unter anderem der mobile Roboter Lio, welcher hauptsächlich im Pflegebereich verwendet wird.

Um die Funktionalität von Lio für eine spezifische Anwendung zu erweitern, kann dieser mit Modulen, sogenannten Add-Ons, ausgestattet werden. Eine dieser zukünftigen Anwendungen wird sein, dass sich Lio in einem Spital, Altersheim oder dergleichen, automatisch an einem beladenem Wäschewagen anhängen und diesen auch ziehen kann. Ein Teil der Arbeit bestand darin, ein Add-On zu entwickeln, welches diese Aufgaben erfüllt.

Der zweite Hauptteil der Thesis bestand darin, die internen unzugänglichen General Purpose Input/Output (GPIO) -Pins von Lio für den Endnutzer erreichbar zu machen, um später externe Hardwarekomponenten zu speisen und zu steuern. Dies wurde durch die Entwicklung eines selbstgemachten PCB erreicht. Das erstellte PCB wurde auch für die Ansteuerung der Aktoren des zu entwickelnden Add-On verwendet, um gleich dessen Funktionalität zu testen.

Bei der Entwicklung des PCB wurde speziell darauf geachtet, gewisse Designregeln einzuhalten, um möglichst gute Resultate in der Thematik EMV- und ESD-Normen zu erzielen.

Die effektive Programmierung des Roboters, um das PCB anzusteuern und den Docking-Prozess auszuführen, wurde sehr schlicht gehalten, da effektive Anwendungen für spezifische medizinische Einrichtungen von F&P selbst umgesetzt werden.

Beim Testen des Gesamtsystems stellte sich heraus, dass gewisse Teilprobleme bestehen bleiben. Im Bereich Elektronik können weitere Massnahmen getroffen werden, um gewisse Normkategorien zu erreichen. Der mechanische Aufbau bedarf je nach Wäschewagen noch Anpassungen, da der momentane Aufbau sehr schlicht und allgemein gehalten wurde.

Zusammenfassend kann jedoch gesagt werden, dass die erreichten Endresultate zufriedenstellend sind. Vor allem die Synergie des erstellten PCB mit dem Add-On bilden eine gute Grundbasis für die Entwicklung weiterer unterschiedlicher Add-Ons, welche integrierte ansteuerbare Aktoren enthalten.

This bachelor's thesis was created in collaboration with the company F&P Personal Robotics. F&P is active in the field of collaborative robotics. One of these robots is the mobile robot Lio, which is mainly used in the care sector.

In order to expand the functionality of Lio for a specific application, it can be equipped with modules, so-called Add-Ons. One of these future applications will be that Lio can automatically attach itself to a loaded laundry cart in a hospital, retirement home, or the like and also pull it. Part of the work was to develop an Add-On that fulfilled these tasks.

The second main part of the work was to make Lio's internal inaccessible GPIO pins accessible to the end user, to later power and control external hardware components. This was achieved by developing a self-made PCB. The created PCB was also used to control the actuators for the Add-On, which is being developed for this thesis, in order to test its functionality.

When developing the PCB, special attention was paid to adhering to certain design rules in order to achieve the best possible results in the thematic EMC and ESD standards.

The effective programming of the robot to control the PCB and carry out the docking process was kept very simple, since applications for special medical facilities are implemented by F&P itself.

When testing the entire system, it became apparent that certain partial problems remained. In the area of electronics, measures can still be taken to meet certain standard categories. The mechanical structure still requires adjustments depending on the laundry trolley, as the current structure was kept very simple and general.

In summary, however, it can be said that the final results achieved are satisfactory. Above all, the synergy of the created PCB with the Add-On forms a good basis for the development of other different Add-Ons, which contain integrated controllable actuators.

Change Control

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Table 1: Change Control

Table of Contents

List of Abbreviations

Abbreviation	Description
PWM	Pulse-Width Modulation
DC	Direct Current
EMC	Electromagnetic Compatibility
PCB	Printed Circuit Board
ESD	Electrostatic Discharge
IC	Integrated Circuit
GPIO	General Purpose Input/Output
FHGR	Fach Hochschule Graubünden University of Applied Sciences of the Grisons
BC	Battery Connector
THT	Through-Hole-Technology
PLA	Polylactide
QR	Quick Response
I/O	Input/Output

Table 2: List of Abbreviations

1 Introduction

1.1 Company

The customer of this bachelor's thesis is F&P Personal Robotics. Founded in 2014 in Zürich, the goal of the founders was to develop robots that support humans and disburden their lives. In 2016, F&P launched with the P-Rob 2, a collaborative and padded robot arm, to the market.

Based on this technology, they developed the assistance robot Lio as a market novelty the following year.

In the subsequent years, F&P developed other systems like the barista robot Barney and founded a new subcompany in Shanghai. However, this bachelor's thesis is only in relation to the assistance robot Lio.

[1]

1.2 Short Description Lio

As mentioned before, Lio is a mobile assistance robot. Its field of application is mostly in the care sector. With his functional gripper arm, Lio supports people in their daily lives and relieves the nursing staff of routine tasks, allowing them to have more time for the residents. In addition, Lio is also able to communicate with the residents and entertain them [2].

To accomplish these tasks, Lio is equipped with different tools and sensors shown in figure 1.

Further information can be found in the user manual file of Lio in the appendix 1.

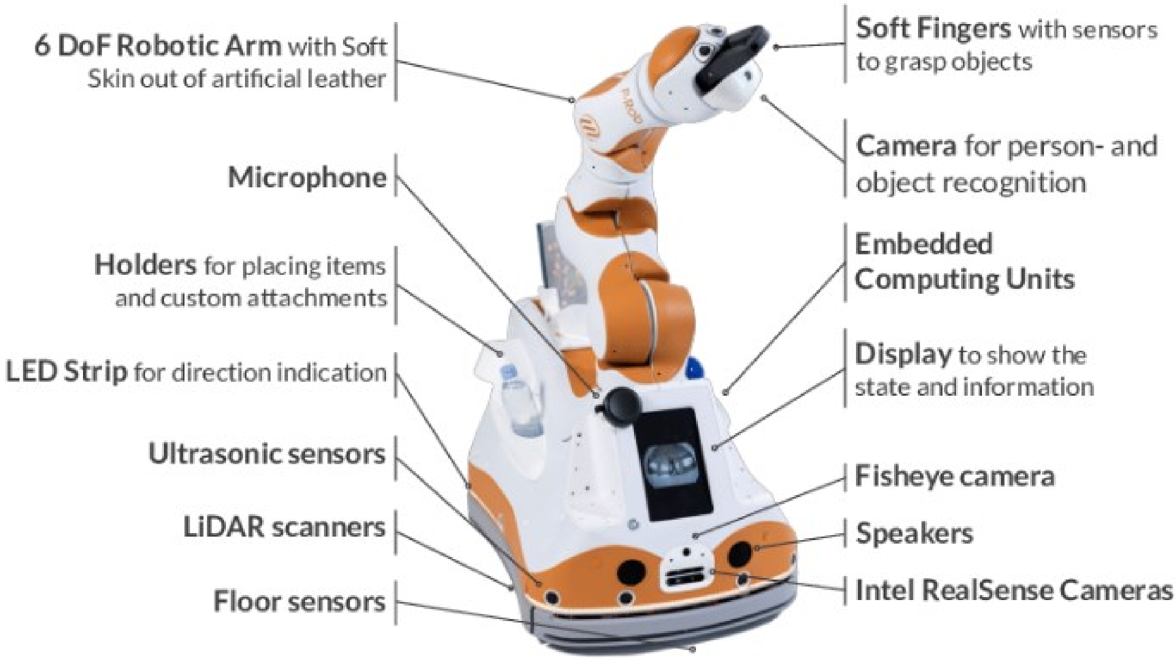

Figure 1: Hardware Lio [3]

1.3 Assignment

The target of the thesis, as described in the fact sheet in appendix 2, is: "Lio can be equipped with several Add-Ons that expand the robot's functionality (for example: water distribution and UVC disinfection tools). Users can also connect their own PC or controller and power it from Lio. To be able to expand these Add-Ons, developing a standard electric interface between the platform and the potential Add-Ons is required."

This electric interface, which offers all the ports and connectors needed to supply and control the further Add-On's, needs to be tested for certain electrical standards like short circuit protection, electromagnetic compatibility (EMC) and shielding. The implementation of the electric interface is facilitated by a self-made printed circuit board (PCB).

In addition to that, during the second kick-off meeting, another assignment was presented. For further applications, Lio needs a system to automatically dock onto certain laundry carts in the nursing field. This system can either be controlled by the previously mentioned electric interface, work just mechanically, or can also use tools like the camera from Lio itself. Only an easy and stable integration into the current system must be guaranteed.

A Lio type B is used for the development process. This is the predecessor of Lio type C. The system developed for Lio type B must be upwardly compatible with type C. The important differences between these two types will become apparent in the course of the work.

1.4 Approach

To make sure that the developer and customer have the same expectations of this project and to get rid of misunderstandings, an exposé will be written. Contents of the thesis, research questions, system boundaries and the timetable with milestone dates will be captured and presented in the exposé and serve as an orientation tool during the whole thesis.

After the exposé presentation, the development of different concepts will begin. To generate inspiration and to find solutions, a market research will be done. After the state of the art is known, a morphological box will divide the system into several problems and different solutions for each of these problems. Advantages and disadvantages for each solution will be presented to highlight their differences. The morphological box then allows the customer to combine the favoured solutions for each problem to generate the final system.

The final combination of these solutions will be developed, built and tested during the whole semester and summer holidays. To guarantee that customer and developer still have the same imagination of the project, the status of the work will shortly be described every week.

All results and steps are recorded in this report. To translate or rewrite certain phrases or terms, DeepL, which is an AI-based online translation service and Chat GPT were used.

2 Clarification of the Task

2.1 Main Tasks

The entire thesis can be divided into three main tasks, each representing one of the three core disciplines in robotics: mechanics, electronics, and software.

2.1.1 Docking to the Cart

Lio must automatically dock onto a laundry cart with its backside. The type of the laundry cart is not specific, and the one shown in figure 2, is as stated in the label, just an example. Therefore, it is crucial that the whole docking mechanism is easily adaptable for different laundry cart designs.

Figure 2: Example Laundry Cart [Own Illustration]

2.1.2 PCB and Electronics

To facilitate the connection of specific ports, such as USB or Ethernet, as well as the GPIO pins from Lio's internal hardware, a PCB, the electric interface, will be designed to serve as an intermediary component.

The PCB and the resulting connections must be short-circuit-proof, and tests for electrostatic discharge (ESD) and EMC standards must be conducted. All tests in the field of EMC and shielding were done in the internal EMC test laboratory of the University of Applied Science of the Grisons (FHGR).

A more detailed description of the hardware of Lio will follow later.

2.1.3 Navigation

The navigation of Lio, for this report, only considers the correct control from Lio to the laundry cart when the cart is in front of Lio. A navigation concept through a whole room to find and dock onto the laundry cart is not part of this thesis and will be done later by F&P itself. Thus, it is important that the navigation solution can easily be adapted.

2.2 Research Questions

From the task description, the following research questions emerged.

- Which components and design ideas can be used to develop a docking system?
- Which possibilities exist to meet standards in terms of electronics?
- What different kind of electronical hardware intersections would be appropriate between the Lio and the Add-On?
- What mechanical design ideas offer a good solution to integrate the Add-On and the interface into the Lio Robot?
- Which techniques can be used to steer the robot to the right position?

The questions serve as a guidance and will be gradually answered throughout the whole report.

2.3 System Boundary

Figure 3 depicts the physical environment surrounding Lio according to the guidelines outlined in the task description. All important components for the tasks are displayed and the interaction between them described with arrows. The system and all associated components developed in this bachelor's thesis are contained within the red dashed lines and are considered as the system boundary.

Note that the Lio is depicted in a simplified manner.

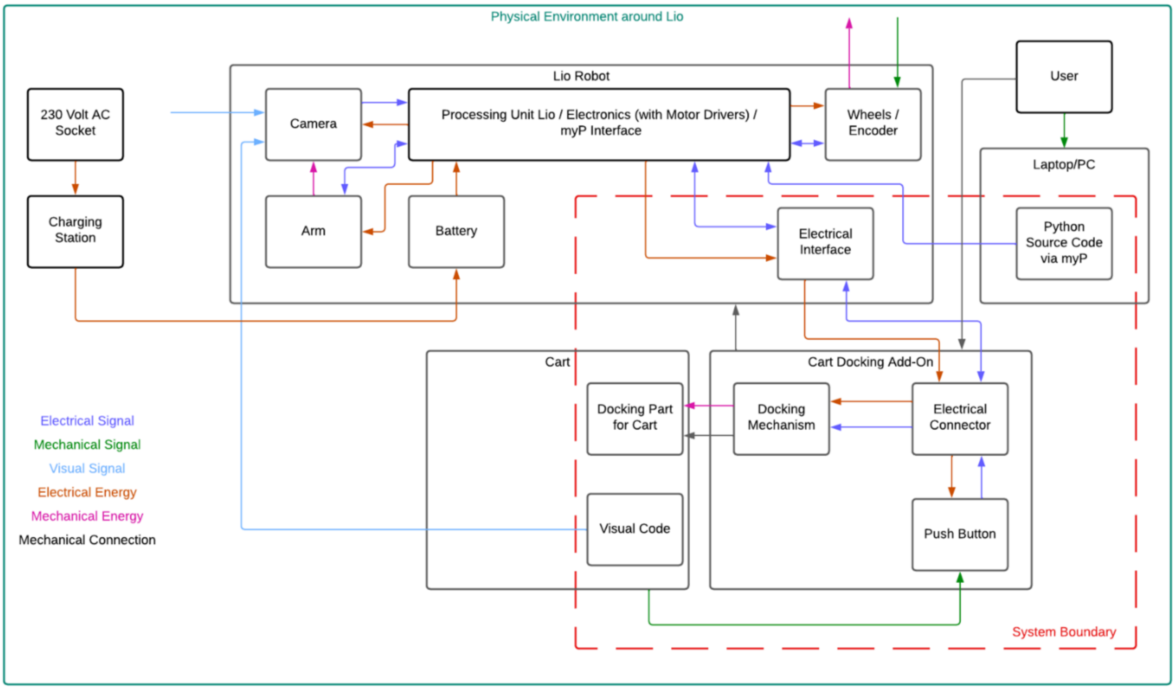

Figure 3: System Boundary [Own Illustration]

2.4 Project Timetable

The timetables of this project can be found in the appendix 3. It consists of two timetables. The first table, called “ideal_Timetable”, is the original plan, which was made at the beginning and served as a rough guide for the entire work. Due to some delays and events the planning changed. The updated timetable with the right timeline is the second table, called “real_Timetable”.

3 Concepts

3.1 Introduction

The clarification of the task outlined that the thesis can be divided into three main tasks, docking mechanism, PCB/electronics and navigation. Each of these main tasks is completed by fulfilling additional subtasks. In this chapter of the report different solutions for these subtasks are documented, compared and finally combined with the help of a morphological box.

While going through the different chapters, state-of-the-art results are mentioned if research has been conducted beforehand for the specific topic.

Additionally, it is important to mention that the concepts only describe the methods or components with which the problems can be solved. It is not specified in this chapter how the actual implementation will take place. This means that calculations, component layouts, and exact costs will be determined during the realization of the final concept.

3.2 Docking Mechanism Concepts

3.2.1 Connection to Cart

Since the type of the final laundry cart is not known, the connection to the cart must be adaptable for various cart designs.

One idea to meet this criterion is by using a **gripper** to grasp the cart. This gripper can either be controlled by a linear or rotational actuator. As possible linear actors, a linear magnetic switch or a normal linear motor can be used. For rotational actors a stepper or a servo motor would be appropriate.

The state-of-the-art research provided different gripper ideas for the linear and the rotational gripper design shown in figure 4 [4].

The position of the grippers to grab different laundry carts can be adjusted in advance by using wing nuts which is roughly displayed in figure 7.

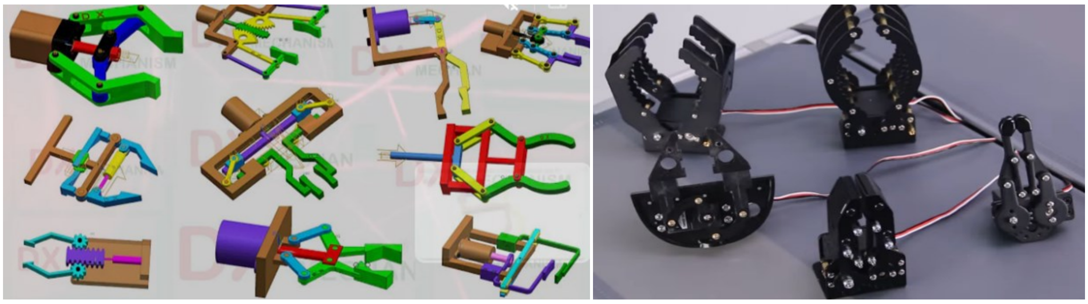

Figure 4: Linear and Rotational Gripper Designs [4]

Another solution would be by developing some kind of **self-locking mechanism**, shown in figure 5. A vertical rod would push the mechanism with the two pushing springs back, until the vertical spring glider slides down, snaps back up, and closes the mechanism without using any additional energy. Nevertheless, one of the previously mentioned actuators is still needed to release the cart again by pulling the slider down. Not to neglect is the fact, that not every laundry cart has a vertical rod with enough free space around it that the mechanism can work properly. Hence, an additional 3D printed part for each cart needs to be developed as a transition piece.

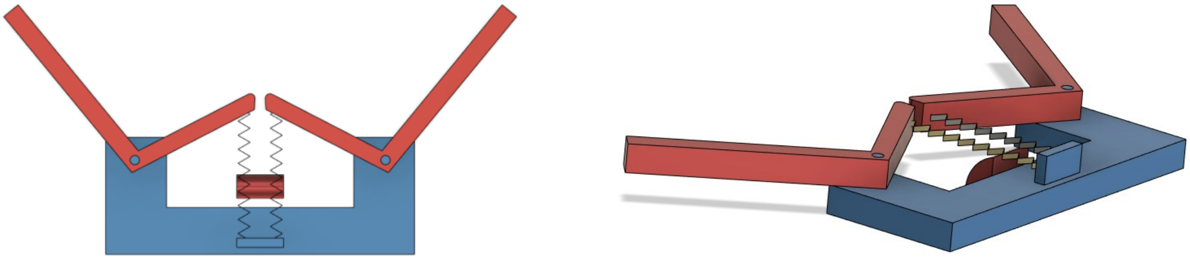

Figure 5: Self Locking Mechanism Draft [Own Illustration]

The last concept to connect to the laundry cart is by using a **magnet** with an additional metal plate which is mounted on the cart. Like the self-locking mechanism, it would be advisable to design and to 3D print specific holders for each cart, allowing the metal plate to be attached to the cart.

3.2.2 Integration into Lio

There are two ways to integrate the mechanical build into Lio. The first way is to develop the whole system in an **Add-On design** way, which can be mounted and dismounted in a single handle, by using the Add-On interface connector, displayed in figure 6. The Add-On Interface connector is permanently mounted on Lio under the brown-coloured Add-On draft in figure 7.

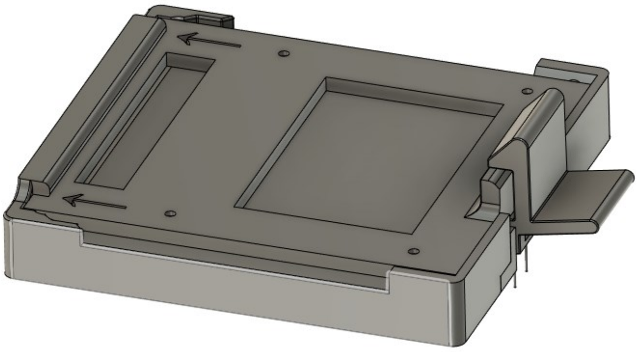

Figure 6: Add-On Interface Connector [Own Illustration]

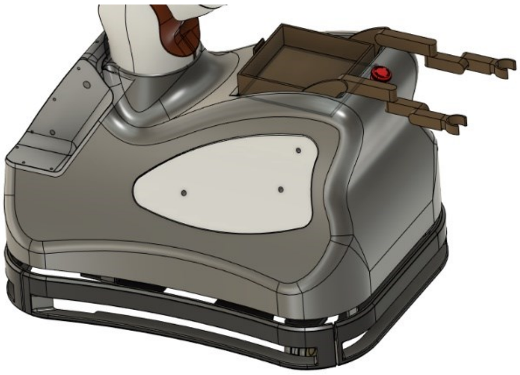

Figure 7: Add-On Design [Own Illustration]

The second way is to mount everything in a **fix design** with the help of the side panel screws of Lio, as shown in figure 8. To move the docking mechanism out of Lio's backspace, an additional actuator would move the mechanism up and down. Finally, a second penetration point is made at the back cover of Lio to connect the GPIO's of the interface with the self-made PCB.

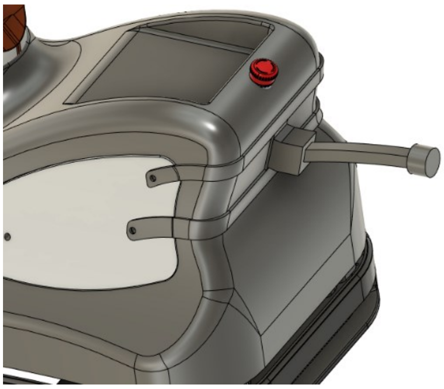

Figure 8: Fix Mounted Design [Own Illustration]

Note that the shown designs are only drafts. They do not imply, that the Add-On design directly comes with the gripper solution and the fix integration design with the electromagnet.

3.2.3 Advantages and Disadvantages

Table 3 shows on the first 3 columns the strengths and weaknesses of the docking mechanisms themselves, from the 4th to the 7th column the possible actuators, and the last two columns summarize the integration designs.

Every docking concept can easily be adapted. The position of the gripper can be altered by readjusting the wingnuts. The self-locking mechanism and electromagnet on the other hand need an additional part on the cart which can also be considered as a disadvantage.

The part "no self-alignment" means that the alignment phase of Lio to dock onto the cart can be tricky. Shown in figure 2, the cart has two vertical rods, to grab these two rods correctly, Lio has to align itself perfectly. Imagine using a magnet with a metal plate on the cart, the alignment of the cart happens automatically through the magnetic force.

Servo, stepper and linear motors offer high torques/forces proportional to the electrical current. This proportionality results in a constant energy supply when choosing the gripper concept where the holding of the cart relies on the force applied by the actuator. In addition, a servo motor increases the current up if the set position is not reached.

An electromagnet also needs constant energy if the connection is only maintained by the magnetic force.

The self-locking mechanism on the other hand only needs energy during the releasing respectively the docking phase.

The control of a servo motor is made with a 50Hz Pulse-Width-Modulation (PWM) signal and is simpler compared to the control of a stepper and linear motor which often need an additional driver hardware. An even simpler control is offered by a linear magnetic switch and an electromagnet by applying a common direct current (DC) voltage.

In the columns "Add-On Design" and "Fix Design" the part "Backspace by Hand" describes the additional space at the back of Lio when the cart docking mechanism is mounted. To free up the backspace of Lio you need to remove the "Add-On Design" by hand in comparison to the "Fix Design" which would have an additional actuator to move the mechanism downwards.

Gripper	Self Locking	Electro-Magnet	Servo Motor	Step Motor	Linear Motor	Linear Magnet	Add-On Design	Fix Design
Easy adaptable	Easy adaptable	Easy adaptable	High Torque	High Torque	High Force	High Force	Add-On Mounted	Screw Mounted
		Control	Control	Control	Control	Control	One Hole into Lio	Two Holes into Lio
Costs	Costs	Costs	Costs	Costs	Costs	Costs		
No self Alignment	No self Alignment	Self Alignment				Integrated Spring	Backspace by Hand	Backspace Controlled
Constant Energy	Sporadic Energy	Constant Energy	Torque ~ Current	Torque ~ Current	Force ~ Current			
	Needs Rod Piece	Metal Part needed	Drives Current			Short Range		

Table 3: Advantages and Disadvantages Docking Mechanism Concepts

3.3 PCB and Electronics

3.3.1 EMC and Shielding

"About 95% of all disturbances are caused by the following kinds of coupling: common use of tracks (galvanic coupling), tracks too close to each other (capacitive and inductive coupling), field influence (radiation coupling)." [5]

Common measures to minimize such problems are: using short cables and twisting them, short and broad paths on PCB, establishing ground layers, separation of analog and digital signals, using only low frequency signals, installation of smoothing capacitors and to secure everything in terms of ESD, the grounding of contact areas is necessary [5].

The measures mentioned above will be implemented without offering them as possible solutions for the customer and should be adhered to in every project involving the topic EMC and shielding. If the standards set by Lio are all met with these measures or with additional possible internal solutions of the FHGR, then no further action will be taken. However, if this is not the case, further measures will be provided to the customer as concept options.

To minimise the radiation coupling around the PCB, the development of a **metallic or ferromagnetic case** around it would be an excellent measure. Or the use of special **shielding tracks** for high current lines on the PCB can reduce the effects of capacitive, inductive and radiation coupling to a minimum. Finally, to also improve the capacitive and inductive coupling a **bigger PCB** can be designed to have bigger space between the tracks.

Not to neglect are also the connections from Lio to the electric interface itself. If the standards are not met with the common measurements, the problem may lie in the connection established by the cable itself. To improve this the use of special **shielded cables** or the **coating** of them with a thin film of conductive material would be appropriate.

3.3.2 Short Circuit Protection

To protect circuits from high loads, a circuit breaker is essential.

"A circuit breaker protects sensitive load circuits from excessive current flow by opening the power supply when the current reaches a predetermined level. The simplest circuit breaker is a **fuse**, but blown fuses require physical replacement. An electronic circuit breaker provides the same measure of circuit protection as a fuse without the single-use problem." [6]

Compared to additional fuses the electronic circuit breaker can be used multiple times but is more complex in its construction. Hence, the question is to implement an electronic circuit breaker as an **integrated circuit** (IC) or to develop a **self-made** version by using multiple different electronic components.

The last and simplest way to guarantee the protection of the circuit is to **rely on the hardware of Lio** itself. Lio is equipped with different fuses for each power rail, which also need to be replaced if an excessive current occurs.

3.3.3 Ports and Connectors Supply

The last question to be answered regarding the electrical interface is, where to exactly offer the ports and connectors on Lio.

One way is to offer the ports somewhere on the plastic cover of Lio by drilling a hole through the cover. To fix the direct cables on the cover **cable bushings** shown in figure 9, would be appropriate. Nevertheless, a more appealing design would be to offer direct ports on the surface of Lio, without having cables all over the place. To accomplish that, two possible design ideas were conceived. The first is to have the PCB placed somewhere inside Lio and the **ports and connectors separated** from it and brought to the surface and held in place with a custom 3D printed construction as shown in figure 11. The second version would be without additional cables from the PCB to the surface but rather having the final **ports directly offered from the PCB** on the cover of Lio, depicted in figure 10. Both constructions would be held in place by securing a nut onto a sleeve with a thread.

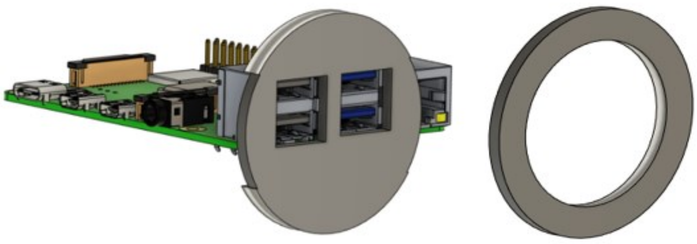

Figure 10: Ports on PCB [Own Illustration]

Figure 9: Cable Bushing [Own Illustration]

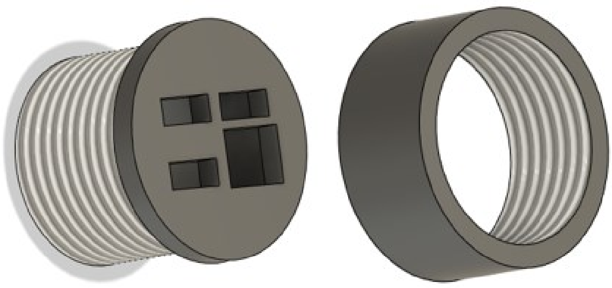

Figure 11: Ports separated from PCB [Own Illustration]

Another approach to offer different ports and connectors on the surface of Lio is to place the **PCB** with the connectors on it **under the Add-On interface**, shown in figure 12. The connection of the GPIO pins to the interface is achieved by using some kind of spring contacts, like the ones shown in figure 13, and the mechanism of the Add-On interface itself.

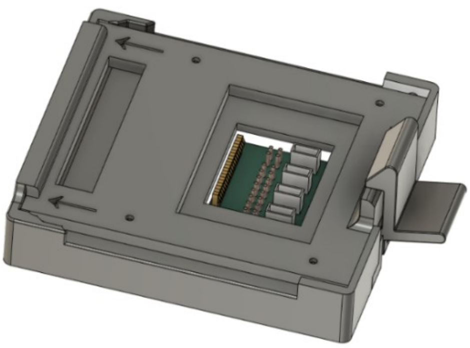

Figure 12: Add-On Interface with PCB [Own Illustration]

Figure 13: Example Spring Contacts [Own Illustration]

3.3.4 Advantages and Disadvantages

3.3.4.1 EMC and Shielding

A case around the PCB must be made out of a difficult to process material and takes up more space in Lio.

Shielded tracks are reliable and will not take away additional space in Lio. But this solution is associated with the delivery of a new PCB.

A bigger PCB, of course, also needs more space, and in addition to that, it is not even guaranteed that the bigger space between the tracks will have a significant enough impact in terms of EMC.

If the standards are not met and the problem arises due to the cables, applying of a thin film of conductive material around them is more cost efficient than replacing them with new shielded cables, as table 4 shows.

Case	Shielded Tracks	Bigger PCB	Shielded Cables	Films / Coating
Mechanic Concept	Simple	Simple	Simple	Simple
Reliable	Reliable	Reliable	Reliable	Reliable
Costs	Costs	Costs	Costs	Costs
Space	Space	Space	Space	Space
Time	Time	Time	Time	Time

Table 4: Advantages and Disadvantages EMC and Shielding

3.3.4.2 Short Circuit Protection

To secure Lio from high currents, the use of additional fusible links requires the customer to replace them manually if a short circuit occurs, as recorded in table 5. However, the replacement takes place on the self-made PCB rather than in Lio's hardware. A reusable circuit breaker is the most convenient option for the customer. Both solutions for the reusable circuit breaker are rather expensive compared to the fusible links, but an IC ensures a reliable and time efficient solution.

Fusible Link	IC	Self-Made CB	Rely on Lio
Simple Usage	Simple Usage	Difficult Usage	Easy Usage
Reliable	Reliable	Reliable	Reliable
Costs	Costs	Costs	Costs
Must be replaced	Reusable	Reusable	Must be replaced
Time	Time	Time	Time

Table 5: Advantages and Disadvantages Short Circuit Protection

3.3.4.3 Ports and Connectors Supply

For every version where the ports and connectors are offered on the cover of Lio, a visible cut out must be done which may result in aesthetic compromises. In addition, every connection to future Add-On's needs to be done with an additional hand movement. Furthermore, it is conceivable that for the version where the ports are directly connected to the PCB and then later also provided somewhere on Lio's surface, that there must be enough space for the PCB itself underneath the casing of Lio.

The placement of the PCB under the Add-On interface does not have any of these drawbacks. Additionally, if the Add-On design solution were to be chosen, the GPIO pin connections would happen automatically with the spring contacts and the Add-On interface mechanism. All mentioned arguments of this chapter are summarized in table 6.

Cable Bushing	Ports direct	Ports on PCB	Under Add-On
Mechanic Concept	Mechanic Concept	Mechanic Concept	Mechanic Concept
Space	Space	Space	Space
Costs	Costs	Costs	Costs
Clumsy Design	Smooth Design	Smooth Design	Smooth Design
Visible Cutout	Visible Cutout	Visible Cutout	Hidden Cutout
Plug in by Hand	Plug in by Hand	Plug in by Hand	Auto Plug in

Table 6: Advantages and Disadvantages Ports and Connectors Supply

3.4 Navigation

To navigate and align Lio to the right position that the mechanism can dock onto the laundry cart, four different solutions were conceived.

The first solution would be to use a **receiver and transmitter**. The specific type of technology, like infrared, ultrasound or radio frequency, would be determined if this solution is chosen. However, it would be advisable to use the already available infrared technology that is needed to navigate Lio to the charging station.

Another solution offers the usage of a **visual code** like an ArUco or quick response (QR) code with the help of the internal camera under the gripper of Lio. The visual code can be printed to a certain size and mounted on the cart. With the internal camera parameters and certain functions, the exact relative position from Lio to the cart can be determined.

To solve the navigation and alignment to the cart with only Lio itself, the already existing **mapping algorithm** can offer a sufficient solution. The position of Lio for each cart placement can be saved in the map if the cart is released. To dock to the specific cart again, the stored position can be accessed.

A different approach is to use some kind of **mechanical guidance**. The mechanical guidance can either be for each cart or a stationary guidance for multiple carts as shown in figure 14.

Figure 14: Mechanical Guidance for Carts [Own Illustration]

3.4.1 Advantages and Disadvantages

Table 7 records that the visual code can easily be implemented but needs to be printed out and placed on each cart. The transmitter and receiver may result in problems due to interferences and reflexions of the emitted waves. The mechanical guidance takes additional space and just relies on the guidance. Hence, if the cart in front of Lio is misaligned too far, there is no other system to avoid a malfunction. The mapping algorithm requires time for a reliable implementation. In addition, it must be guaranteed, that the cart is not moved from its position which was saved by Lio.

Visual Code	Transmitter and Receiver	Mechanical Guidance	Mapping Algorithm
Implementation	Implementation	Implementation	Implementation
Costs	Costs	Costs	Costs
No additional Energy Supply	Additional Energy Supply	No additional Energy Supply	No additional Energy Supply
Additional Component	Additional Component	Additional Component and Space	No Additional Component
		Works only in specific orientation threshold	Works only if Cart is not moved

Table 7: Advantages and Disadvantages Navigation Concepts

3.5 Morphological Box and Choice

Normally with the help of a morphological box, like table 8, different solutions are combined, and complete concepts can be presented by leading a track with a specific colour through the box. Nevertheless, for this thesis the morphological box only serves as a good overview for every solution for each part. Therefore, it was decided not to use ready-made concepts. The reason for this approach is that every solution for each part of the thesis can be combined with every other solution and the customer should not be restricted to pre-made concepts.

It is even allowed for the customer to combine certain solutions of one specific task. For example, in the docking concept, it is possible to develop a hybrid version of the self-locking mechanism and the electromagnet. The magnet would guarantee a correct and guided connection by pulling the cart until the self-locking mechanism hooks on. Then the magnet can be switched off to save energy.

The cost thresholds for each solution are due to the uncertainty over which final combination of solutions will be chosen. Hence, it is unclear how the components must be designed to interact with each other, and an accurate cost summary will be determined later.

Task	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
Docking Concept	Gripper 5-20 CHF	Self-Locking 5-25 CHF	Electromagnet 8-20 CHF		
Actor	Servo Motor 15-40 CHF	Step Motor 20-60 CHF	Linear Motor 40-100 CHF	Linear Magnet 15-40 CHF	Electromagnet 8-20 CHF
Integration into Lio	Add-On Design	Fix Design			
Material	PLA 1-2 CHF	ABS 1-2 CHF	Aluminum 15-25 CHF		
EMC and Shielding	Case 5-60 CHF	Shielded Tracks 30-40 CHF	Bigger PCB 30-40 CHF	Shielded Cables 20-50 CHF	Films / Coating 20-30 CHF
Short Circuit Protection	Fusible Link 0.2-2 CHF	IC 1-4 CHF	Selfmade CB 3-4 CHF	Rely on Lio 0 CHF	
Ports and Connectors Supply	Cable Bushing 0.2-3 CHF	Ports on PCB 0.1-0.2 CHF	Ports directly Plugged in 0.1-0.2 CHF	Under Add-On Interface 0.1-0.2 CHF	
Navigation for Docking	Visual Code 0.5-2 CHF	Mapping 0 CHF	Receiver Transmitter 10-50 CHF	Mechanical Guidance Cart 10-100 CHF	

Table 8: Morphological Box

3.6 Concept Decision

Table 9 shows the final combination of all concepts for the final solution.

To guarantee that the docking process occurs smoothly and reliably the usage of the electromagnet is very suitable for this. To avoid a constant energy consumption the connection is maintained by the self-locking mechanism.

To release the cart from the self-locking mechanism a linear magnet is sufficient.

The whole design will be constructed as an Add-On out of polylactide (PLA) with a 3D printer.

If the standards in terms of electronics are not met with the common measurements or internal solutions of the FHGR, a new PCB will be ordered with special shielded tracks and the existing cables will be coated with a thin film of conductive material.

Safety in terms of excessive currents, is ensured by using different IC's which can be used multiple times.

All ports and connectors will be supplied under the Add-On interface to avoid visual cutouts on the cover of Lio.

To navigate Lio to the right docking position, all carts will be equipped with visual codes.

Task	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
Docking Concept	Gripper 5-20 CHF	Self-Locking 5-25 CHF	Electromagnet 8-20 CHF		
Actor	Servo Motor 15-40 CHF	Step Motor 20-60 CHF	Linear Motor 40-100 CHF	Linear Magnet 15-40 CHF	Electromagnet 8-20 CHF
Integration into Lio	Add-On Design	Fix Design			
Material	PLA 1-2 CHF	ABS 1-2 CHF	Aluminum 15-25 CHF		
EMC and Shielding	Case 5-60 CHF	Shielded Tracks 30-40 CHF	Bigger PCB 30-40 CHF	Shielded Cables 20-50 CHF	Films / Coating 20-30 CHF
Short Circuit Protection	Fusible Link 0.2-2 CHF	IC 1-4 CHF	Selfmade CB 3-4 CHF	Rely on Lio 0 CHF	
Ports and Connectors Supply	Cable Bushing 0.2-3 CHF	Ports on PCB 0.1-0.2 CHF	Ports directly Plugged in 0.1-0.2 CHF	Under Add-On Interface 0.1-0.2 CHF	
Navigation for Docking	Visual Code 0.5-2 CHF	Mapping 0 CHF	Receiver Transmitter 10-50 CHF	Mechanical Guidance Cart 10-100 CHF	

Table 9: Concept Decision

With the final system compilation, the implementation of each individual discipline is now documented in the following chapters. As will soon be recognised, the tasks and objectives have been adjusted slightly, as certain insights were gained during the implementation and further meetings.

4 Electric Interface

Electrical components are referenced with their manufacturer number in the following chapters. In addition, appendix 4 contains direct links of the components to the Mouser homepage where data sheets and further information can be found. All files in terms of the created PCBs can be found in appendix 5.

4.1 Redefined Task

The chapters 2 and 3.6 showed that internal interfaces of Lio such as USB connections but also the GPIO pins are routed to the surface with the help of the electrical interface.

Due to the fact, that the routing of the USB connectors would only be a simple plug-in transition from the inside of Lio to the PCB and then to the surface of Lio, it was decided not to offer USB connections on the PCB. Therefore, the PCB will only ensure the usage of the intern GPIO pins of Lio.

In addition, it was agreed that the electric interface should offer three different voltages, 3.3, 5 and 12 volts to control or to supply certain things in the future with it.

4.2 Electrical Construction Knowledge of Lio for further Procedure

This chapter describes all important electrical parts of Lio to understand why certain features are present in the interface as they are. All information and figures listed in this chapter can be found in the file “P-Rob 3 User Manual” in appendix 1 or in [7].

4.2.1 P-Rob 3

As seen in figure 1, Lio is equipped with a robotic arm, the P-Rob 3. The GPIO pins mentioned during the work are provided by the P-Rob 3 and can be seen slightly at the top left of the back panels as the three white slim connectors in figure 15.

Figure 15: P-Rob 3 Overview [7]

4.2.1.1 Usage of Inputs/Outputs (I/O's) P-Rob 3

The three previously mentioned connectors can now be better seen in figure 16 and are the digital inputs/outputs and I/O power connectors.

Before the digital outputs are usable, it is essential to attach a voltage of 10 to 36 volts to the I/O power connector. The outputs are controlled with the myP interface of F&P with the help of a high side switch and offer the voltage applied at the I/O power connector at the output, if the high side switch is switched on.

The myP interface will be described more precisely in the chapter 6.1. Currently it is only important to know that myP is a python-based web editor equipped with different functions and applications to control Lio and of course to also handle the I/O's of P-Rob 3.

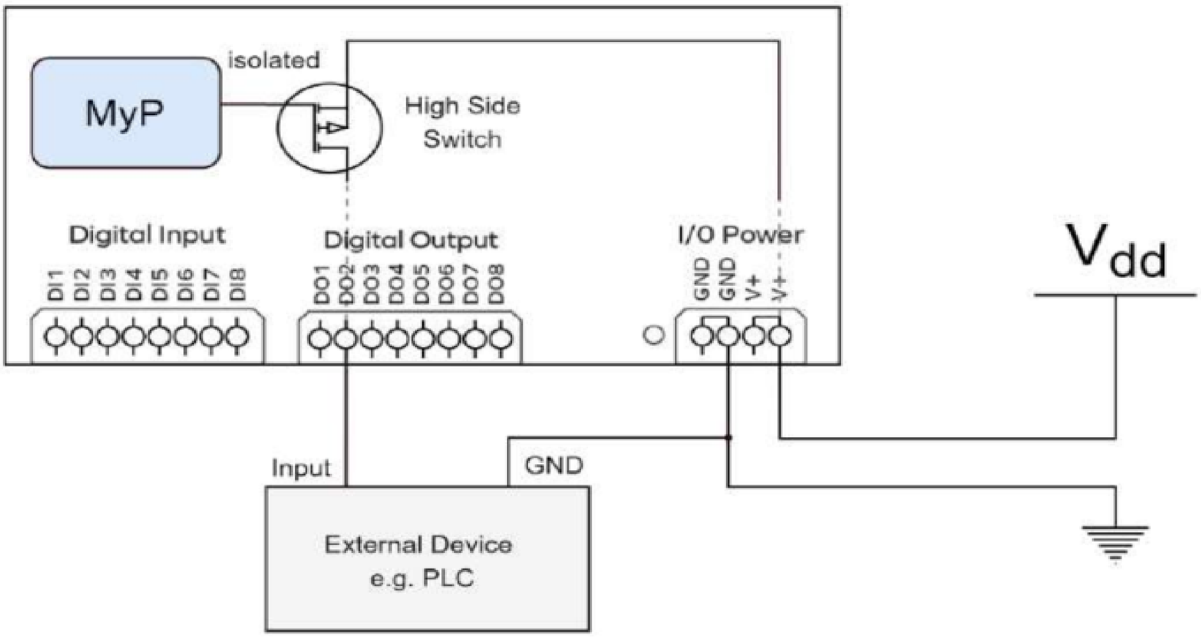

Figure 16: Digital Outputs P-Rob 3 [7]

Good to know, the maximum output currents of the DO1-DO6 are 0.25 amperes each. DO7 and DO8 are suitable for inductive loads up to two amperes each. Nevertheless, those values will never be reached due to the layout of the electric interface as will be seen later on.

The usage of the digital inputs is very simple. By applying a voltage between 10 and 36 volts, the myP interface interprets the value as a high signal. Below three volts, myP will read this pin as a low signal. Figure 17 shows an example usage with a PNP transistor.

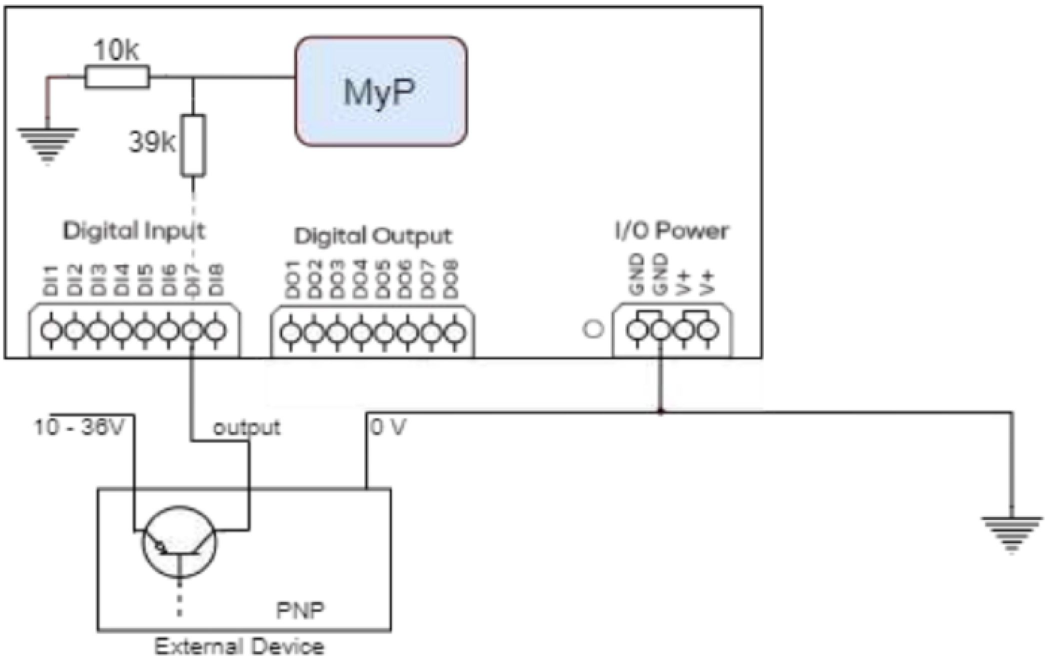

Figure 17: Digital Inputs P-Rob 3 [7]

4.2.2 Power Lio

In the file "62-0382" in the appendix 6, the mobile platform of Lio type B is equipped with different power rails which convert the battery voltage of Lio down to different voltages like 12 or 19 volts.

The Lio type C, on the other hand, does not possess such power rails with fixed voltage values but has multiple connections directly to the battery voltage. The battery voltage can range from 23 volts when empty up to 29 volts if fully charged.

Since the electric interface will also be used on a Lio type C, it is important that the whole system can deal with voltages up to 30 volts!

4.3 Power Supply Entry Electric Interface and I/O's Lio

The voltages of these previously mentioned power rails can be tapped with special connectors with the manufacturer number 1445022-2, respectively 2-1445100-2 as the counterpart.

The voltage of the power rail is now connected to the PCB via a cable to the connector shown in figure 18, called "BC" battery connector, which is the same connector type as the power rail. This voltage on the "BC" connector will supply the whole electric interface.

To protect the electric interface and further components from short peak voltages, a cera diode "D_30V" was used in the layout.

To avoid reverse voltages three parallel Schottky diodes were used in series.

The voltage after these protection measures is called "V_Battery" due to the fact that the connector "BC" will be directly connected to the battery when the interface is used in a Lio type C. "V_Battery" will be mentioned multiple times during this part of the paper and it should be pointed out again, that this voltage can vary from 23 to 29 volts.

Furthermore, as can be seen in the figure 18, that there is a fuse in series with the "Supply_P_Rob_3_GPIO" connector. This connector, with the manufacturer number 1814867, is the same type as the "I/O Power" connector from P-Rob 3 shown in figure 16 and 17. These two, four headed male plugs from the P-Rob 3 and the electric interface are connected via cables with the help of their counterparts with the number 1704857.

Hence, this connection supplies the digital outputs shown in figure 16 and makes them usable. The fuse protects the internal digital output circuit of the P-Rob 3 from a short circuit and will trip at a current of 350mA and then recover on its own.

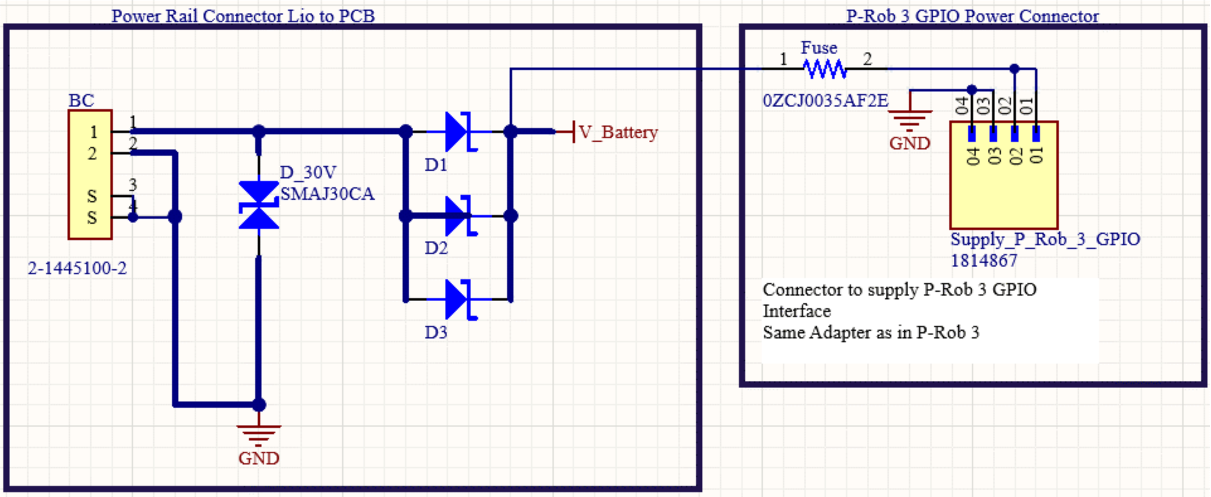

Figure 18: Power Supply Entry [Own Illustration]

4.4 I/O Connectors from Lio to PCB

In figure 19, there are two connectors of the same type as shown in figure 16 with the part number 1814906. These connectors on the PCB are directly connected via cable with the of P-Rob 3 connectors with their counterparts 1704861.

It is important to mention that the numbering of the connectors is mirrored on the PCB compared to the P-Rob 3 connectors. This was done to avoid the twisting of the cables to the pluggable counterpart connector 1704861.

Therefore, if the myP interface enables an output, the voltage will be present at the corresponding output pin of the connector. The same applies to the "Input Lio" connector, if a certain voltage is applied at one of the pins, it can be read by the myP interface.

Last but not least, it is important to remember for the further functionality of the electric interface that DO1-DO7 respectively DI1-DI4 are nothing more than the direct connections to the digital input/output connectors seen in figure 16 and 17.

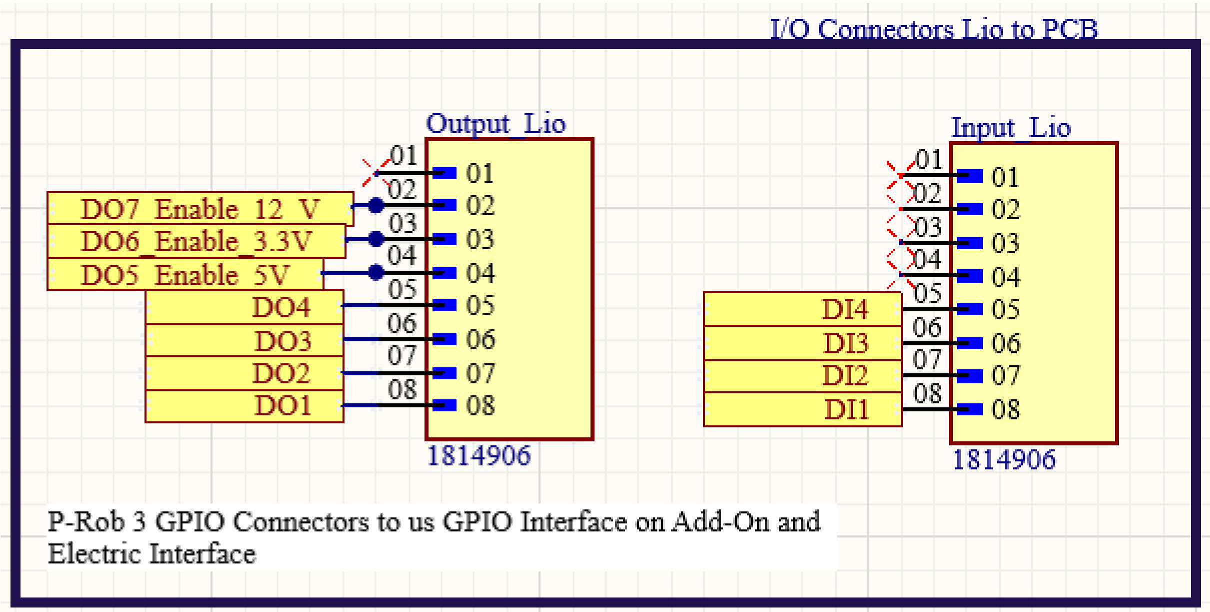

Figure 19: I/O Connectors from Lio to PCB [Own Illustration]

4.5 Buck Converter

To convert the voltages to the desired values, the TPS62933ODRLR buck converter was used. The following design was created with the help of the data sheet and can be found in the appendix 7 or in [8]. The data sheet provides ready-made designs for the output voltages of 3.3, 5, and 12 volts at page 32. Nevertheless, these values were slightly adapted with mathematical formulas or with the help of the Webench Power Design Tool of Texas instruments, linked on page 29 of the data sheet.

Only the 5 volts buck converter is presented in the documentation, as the other buck converters only differ in a voltage divider and in that the 12 volts converter has a 1.2MHz switching frequency compared to the other two with only 500kHz.

The schematic of the buck converter was split in half to guarantee a clear overview and can be seen in the figure 20 and 21.

4.5.1 VIN

The previously mentioned voltage "V_Battery" is connected to the VIN pin of the buck converter and will be converted down to a certain value. The TPS62933ODRLR has an input voltage range from 3.8-30 volts DC.

The device requires an input decoupling capacitor of approximately 20µF between the input voltage VIN and ground GND, to smooth out voltage fluctuations and noise to guarantee a stable supply voltage. In addition, to filter high frequency noise, a smaller capacitor of 0.1µF is recommended to be connected in parallel.

4.5.2 EN

To enable the buck converter, the pin EN can be driven high or be left as a floating pin. EN considers a voltage of above 1.21 volts as a rising edge and a voltage below 1.17 volts as a falling edge. The absolute maximum ratings for this pin are -0.3 to 6 volts.

Hence, an external resistor divider was implemented to protect the pin from a voltage which is too high. Remember, the "DO5_Enable_5V" is the voltage which is switched on with the myP interface and will have the same value as "V_Battery" and can therefore reach values of up to 29 volts. But if a power rail is used for the power supply, the voltage "V_Battery", hence "DO5_Enable_5V" can also only be 12 volts. For both cases, this voltage must be in the threshold of 1.21 – 6 volts to be considered as a high signal for EN.

$$EN = \frac{R2 * DO5\_Enable\_5V}{\mathrm{R1} * \mathrm{R2}}$$

Formula 1: Resistor Divider

By applying formula 1 with the maximum voltage of "DO5_Enable_5V" with 29 volts, the voltage at EN will be around 4.2 volts and is still under the maximum value of 6 volts. If "DO5_Enable_5V" is only 12 volts, EN will be around 1.74 volts, which is still considered as a high signal.

4.5.3 SS/PG

"The SS pin of TPS62933ODRLR is used to minimize inrush current when driving capacitive load. The devices use the lower voltage of the internal voltage reference, "VREF", or the SS pin voltage as the reference voltage and regulates the output accordingly. A capacitor on the SS pin to ground implements a soft-start time. The device has an internal pullup current source that charges the external soft-start capacitor." [8]

This section of text might seem a little confusing at first, important to know for this report is only, that a soft start time protects the circuit from high inrush currents at the output of the buck converter when driving a large capacitive load, by slowly increasing the output voltage over a certain time. The briefly mentioned "VREF" is an internal reference voltage of 0.8 volts within the buck converter and does not need to be explained in more detail.

SS/PG cannot be left floating and a minimum of 6.8nF must be connected to this pin. With formula 2, the t_{SS} will be approximately 1ms when I_{SS}, the typical intern pullup current, is considered around 5µA as described in the data sheet.

For the application of the electric interface, the soft start time of each buck converter is around 3.2ms and is a recommended value for typical applications, as suggested by the previously mentioned Webench Power Design Tool from Texas Instruments.

$$t_{ss} = \frac{C_{SS} * V_{REF}}{I_{SS}}$$

Formula 2: Soft Start Time

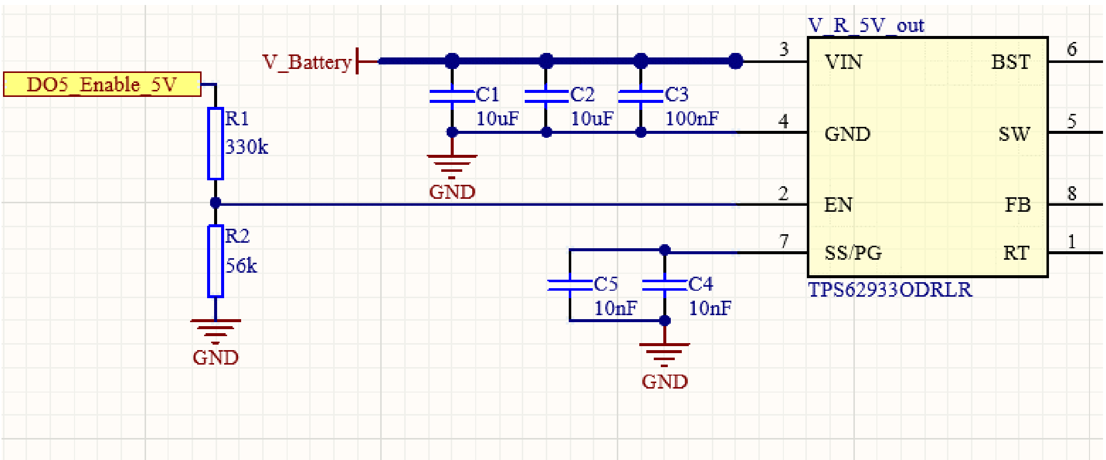

Figure 20: Buck Converter Circuit left [Own Illustration]

4.5.4 BST

The capacitor voltage C6 reflects the internal bias voltage of an integrated high-side MOSFET. The exact functioning of this mechanism can be found in the data sheet, and only the use of this pin is briefly considered.

The voltage at the capacitor is needed to protect the output of the buck converter from short circuits by comparing the regulated voltage with the nominal voltage of the output and the capacitor must be a 100nF ceramic capacitor. If the regulated voltage is only 65% of the nominal voltage the internal overcurrent mechanism will be triggered, and the buck converter will be switched off. The same applies to overvoltage, if the regulated voltage is 115% of the nominal voltage the switching will be turned off until 110% of the nominal voltage is reached.

4.5.5 RT

RT determines the switching frequency of the device. Floating results in 500kHz, tying to GND results in 1.2MHz. In addition, it is possible to connect a timing resistor to it to have specific switching frequencies. To mention is, that only the 12 volts buck converter was tied to GND to guarantee, that every buck converter can operate with the same type of inductor.

4.5.6 SW

SW is the switching output of the converter. To determine the inductor formula 3 can be used. The data sheets recommend that ΔI_L of the current after the inductor should be around 40% of the maximum output current. With a maximum output current of three amperes, this would be around 1.2 amperes. With f_{sw} as the switching frequency set by RT the proper inductance is around 6.8µH.

$$\Delta I_L = \frac{\mathrm{V_{Out}} * (V_{In_{Max}} - V_{Out})}{V_{In_{Max}} * L * f_{sw}}$$

Formula 3: Ripple Current

To compute the effective maximum voltage ripple at the output, formula 4 can be used and is composed of two parts. ΔV_{OutESR} is caused by the inductor current ripple in series with the resistance of the output capacitors. According to the data sheet of the 100nF capacitor C7, in appendix 8, the ESR at a frequency of 500kHz is around 0.1Ω. Hence, ΔV_{OutESR} will be around 0.12 volts.

ΔV_{OutC} on the other hand, is caused by the current ripple of the coil charging and discharging the output capacitors and is around 0.007 Volt. Due to the fact, that those two voltage ripples are not in phase, the actual peak-to-peak voltage ripple is smaller than the sum of both together and will still be around the 0.12 volts.

The measured values of the ripple voltage will be documented later in the chapter 4.11.

$$\Delta V_{OutESR} = \Delta I_L * ESR$$

$$\Delta V_{OutC} = \frac{\Delta I_L}{8 * f_{SW} * C_{out}}$$

Formula 4: Ripple Voltage

4.5.7 FB

FB is the output feedback. The voltage at the output can be set to a fixed value by using the voltage divider R3, R4 and R5. The data sheet of the TPS62933ODRLR recommends using a 10kΩ resistor for the lower part of the voltage divider, here with R4 and R5. After that the upper resistor, in this case R3, can be computed with formula 5. Remember, V_{Ref} is still the previously mentioned 0.8 internal reference voltage of the buck converter. Normally, a 10kΩ resistor is not necessarily used for the lower resistor, instead, both must be matched to each other, as shown in figure 21.

$$R_{upper} = \frac{\mathrm{V_{out}} - V_{Ref}}{V_{Ref}} * R_{lower}$$

Formula 5: Output Voltage Divider

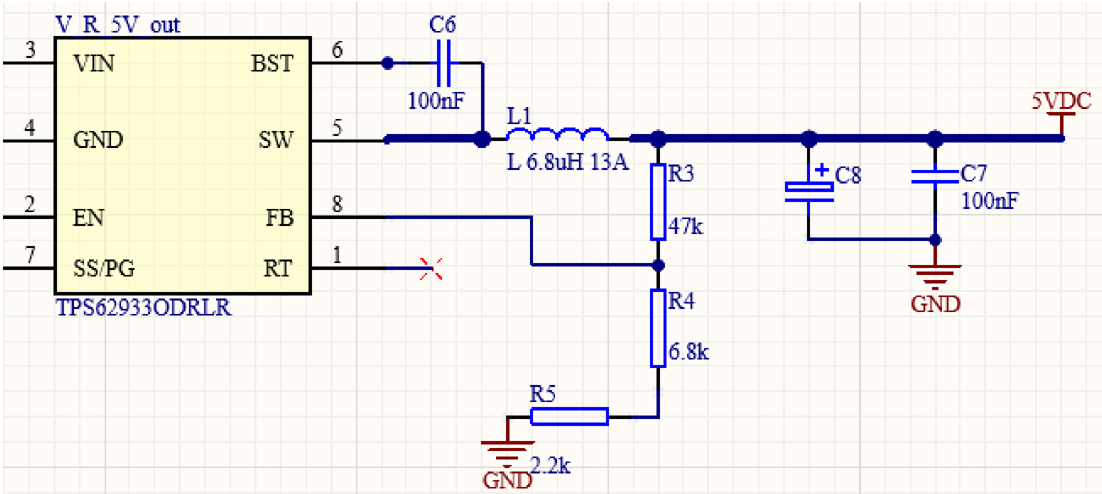

Figure 21: Buck Converter right [Own Illustration]

4.5.8 Recapitulation

The three buck converters can be switched on with the myP interface by applying a voltage over the voltage divider on the EN pin. Therefore, if myP does not enable the buck converter, the output, in this case "5VDC", is tied to GND.

Each buck converter can drive currents of up to three amperes and if a short circuit occurs the buck converter switches off automatically.

4.6 Output Device Control

The electric interface offers the possibility to control four different devices with the help of four MOSFET n-channels with the manufacturer number PMV45EN2R. To use a device, for example, an electromagnet, the positive pole of the electromagnet can be connected with one of the three voltages provided by the buck converters and the negative pole of the electromagnet with one of the four DO-_Device_# connections, as shown in figure 22.

If the MOSFET is switched on via a voltage divider with the myP interface on one of the four DO# pins, the current can run through the device.

The voltage divider on the gate of the MOSFET is due to the fact that the voltage on DO# can be up to 29 volts and the maximum gate-source voltage is only 20 volts. The drain-source voltage can be up to 30 volts with a current of up to 5 amperes but will never reach this value due to the short circuit protection of the buck converter which will be triggered by three amperes.

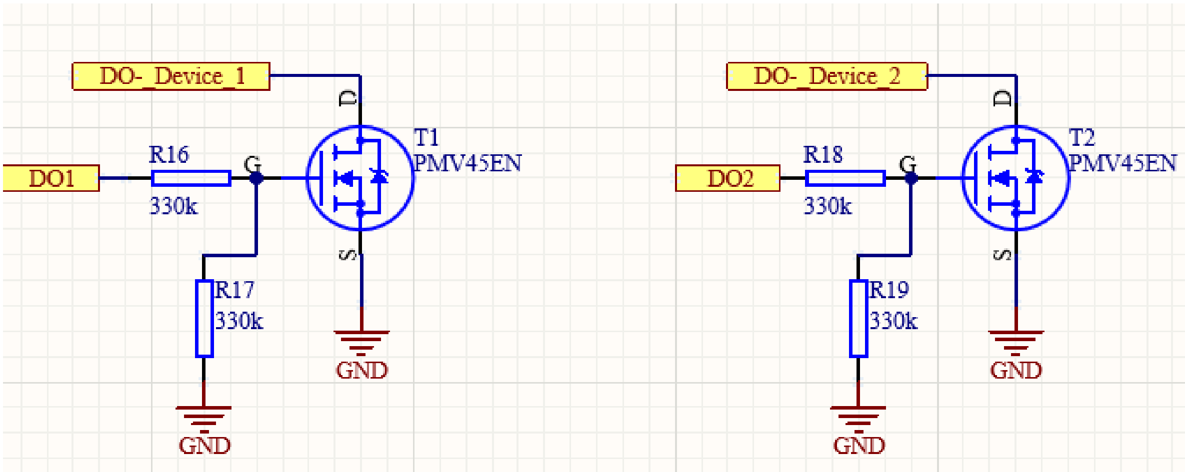

Figure 22: Output Control Circuit [Own Illustration]

4.7 End User Access

4.7.1 Header Pins

The easiest way to use the electric interface is through the two times eight header pins which are shown in figure 23. As mentioned before, the 3.3, 5 and 12 volts voltages can only be used if they are switched on via the myP interface. External devises can be used as described in the last chapter. The digital inputs are even simpler to use. By applying a voltage of above 10 volts, myP offers the possibility to read this as high signal.

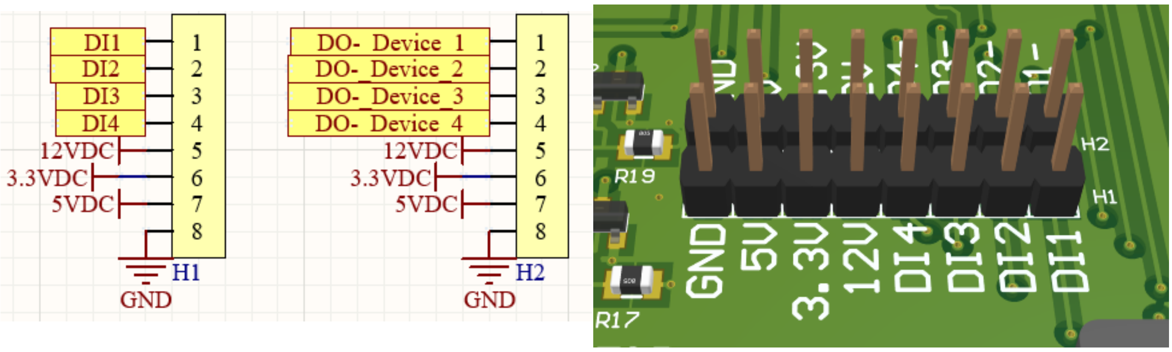

Figure 23: Header Pins Electric Interface [Own Illustration]

4.7.2 Spring Contacts

Another way to use the electric interface is via the spring contacts. Each spring contact, shown in the right part of figure 24, is one specific electrical contact, shown in the schematic part of the figure.

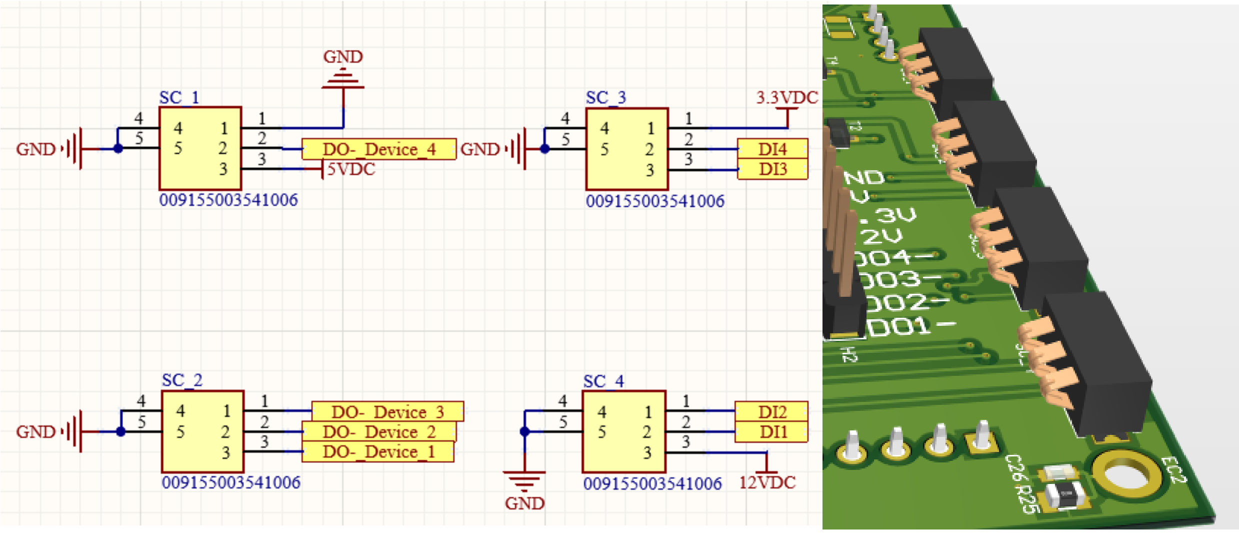

Figure 24: Spring Contacts [Own Illustration]

To establish the electrical contact and to actually use them in a practical, way an additional PCB counterpart was made in the form of a hole plate shown in figure 25. The electrical connection will be established via the spring contacts and the rectangular golden sliding contact of the spring counterpart. The holes of the spring counterpart can be used to make a circuit for a specific application, which is described in the next chapter in the form of an example. How the spring counterpart will be held in place and how it will interact with the electric interface will be shown in the chapter 5.

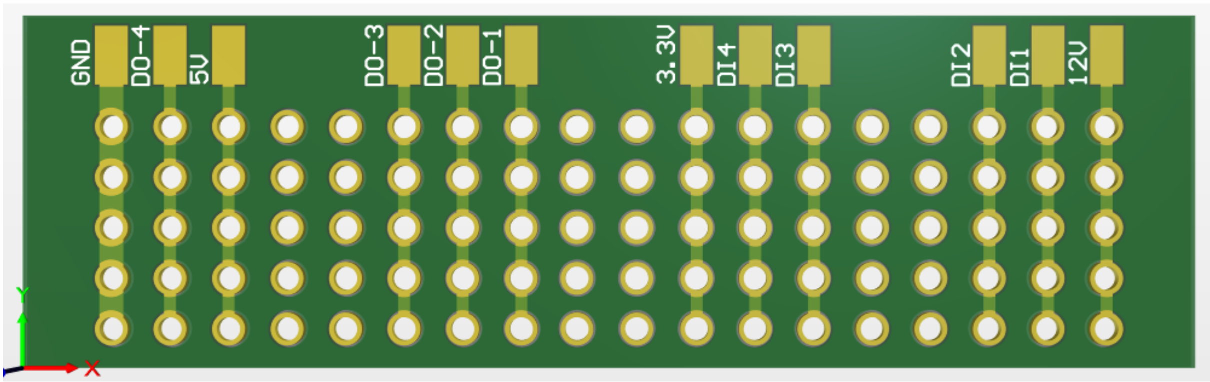

Figure 25: Spring Counter Part [Own Illustration]

4.7.3 Example Usage Slider Part for Cart Docking Mechanism

For the example use of the slider part, an electric linear magnetic switch is controlled, and a push button is read out with a 12 volts signal.

The two push button connections are connected to the black and white cables running out of figure 26. The contact "DI1" on the right is pulled down to "GND" via the resistor and the black horizontal cable. If the button is pushed, an electrical current runs through the resistor and a 12 volts voltage is applied to "DI1".

To control the linear switch, the anode is connected to "5V" and the cathode to "DO-1". "DO-1" is nothing else than "DO-_Device_1" shown in figure 22. If "DO1", also shown in figure 22, is switched high, the cathode of the switch is connected to "GND", and an electrical current can run through the device. To protect the system from voltage peaks of the magnetic switch, a freewheeling diode was also installed between "5V" and "DO-1".

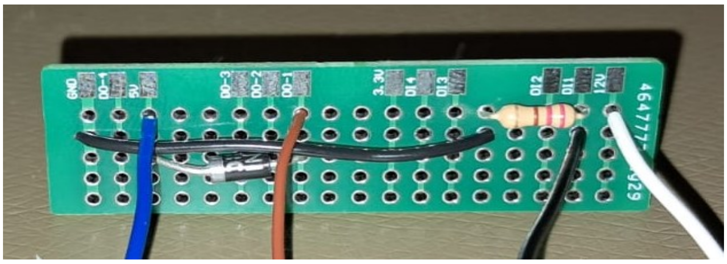

Figure 26: Example Usage Slider Part [Own Illustration]

4.8 Grounding of Electric Interface

Lio's grounding concept is based on a common ground throughout the robot. This common ground is connected to the earth via the wheels of Lio. In addition, internal metal parts of the construction are also connected to the ground. To guarantee, that the electric interface shares this common ground, a plated pad was used.

The plated pad has a hole with a diameter of 2.6mm with an electrical contact area. These holes can be found at every corner of the PCB and are used as mounting holes. The screws that mount the PCB are screwed into the metal frame of Lio which is connected to the earth as previously mentioned.

By connecting the contact area "EC1", shown in figure 27, the earth will be connected to ground via a capacitor of 1µF and a resistor of 1MΩ in parallel to avoid a short circuit if the potential difference is large. Hence, it is guaranteed that the GND of the electric interface shares the common GND of Lio.

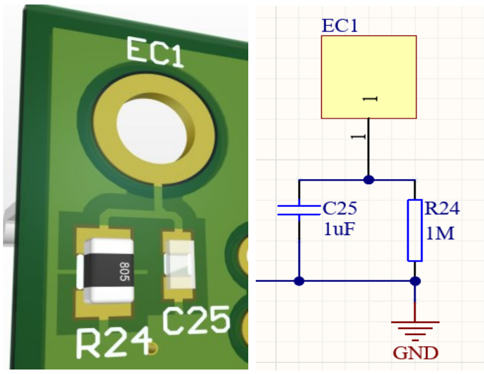

Figure 27: Earth Connection [Own Illustration]

4.9 Layout

4.9.1 Overview

On the right side of the figure 28, the PCB is turned 180° around its vertical axis.

This side is the bottom side of the PCB where all the connectors are mounted.

Common layout measures described in chapter 3.3.1 were met in the current design. The only measure that was not adhered to was using short paths on the PCB from the output of the buck converter to the actual end user access places.

It is easy to recognise, that the buck converters are on the left side of the PCB and the header pins and spring contacts are on the right side. Hence, the path, especially to the spring contacts, are very long. However, this was done deliberately due to the fact that the header pins and spring contacts need to be reachable for the end user but also need to be covered with some kind of the same lid when unused as described later on in the chapter 5.

The logic behind the electric interface was already described in the previous chapters and where exactly which component is placed is no longer explained in detail. The following chapters will only cover the layer structure and the layout of the buck converters.

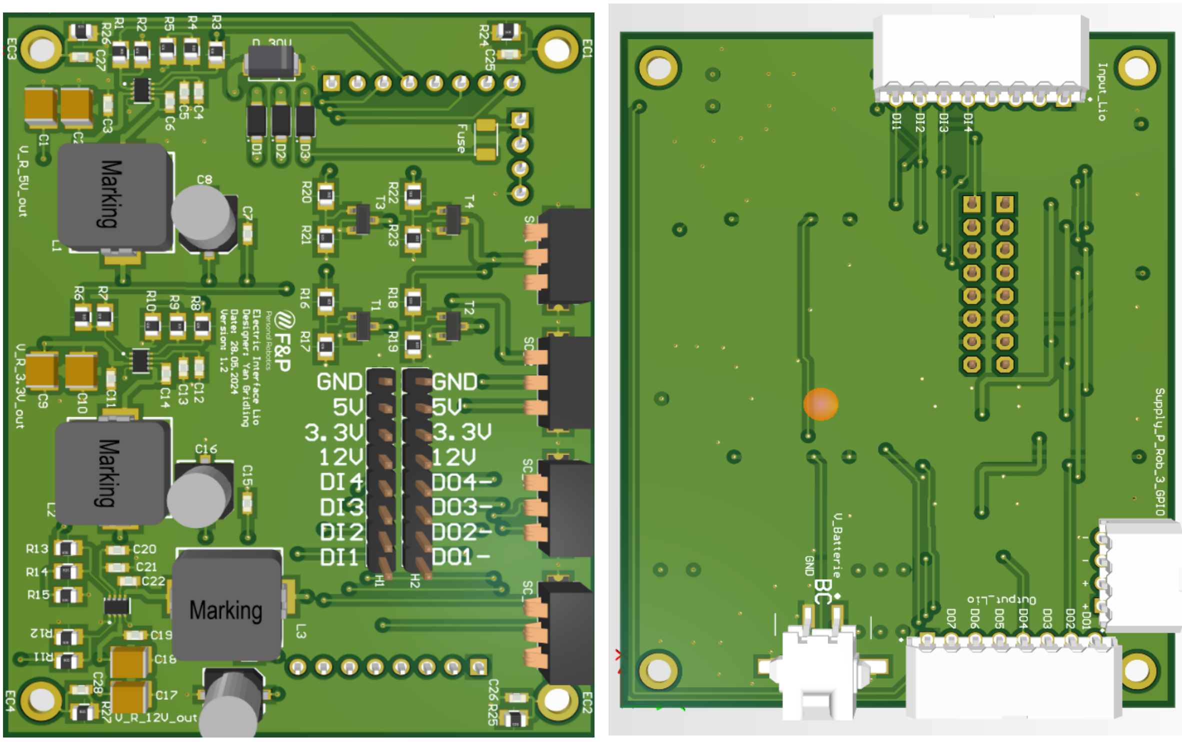

Figure 28: Electric Interface Overview [Own Illustration]

4.9.2 Layer Structure

The electric interface is a four-layer PCB. The first layer called “Vertical Connection Lines”, is mostly used for vertical lines, particularly if the lines have to cover a long distance and only if it makes sense.

The second layer is the ground layer and ensures short connection lines to the ground for each component.

Layer three is called “Power Lines” and establishes the connections for the input voltage of the power rail or battery, and the 3.3, 5 and 12 volts power lines. Either the power lines have a thickness of 0.508mm or are present as polygons.

The last layer, layer four, is used for the horizontal connection lines.

Unused areas of each layer of the PCB were also poured into polygons and connected to ground. This improves ESD ratings, because possible open contact areas are directly connected to ground. In addition, this also improves EMC, as the high-current supply lines in particular are surrounded by ground surfaces, creating a ground shield.

4.9.3 Buck Converter Layout

The following layout guidelines are written in the data sheet of the buck converter.

“• Place the inductor, input and output capacitors, and the IC on the same layer.

• Place the input and output capacitors as close as possible to the IC. The VIN and GND traces must be as wide as possible and provide sufficient vias on them to minimize trace impedance. The wide areas are also of advantage from the view point of heat dissipation.

• Place a 0.1-µF ceramic decoupling capacitor or capacitors as close as possible to VIN and GND pins, which is key to EMI reduction.

• Keep the SW trace as physically short and wide as practical to minimize radiated emissions.

• Place a BST capacitor and resistor close to the BST pin and SW node. A > 10-mil width trace is recommended to reduce the parasitic inductance.

• Place the feedback divider as close as possible to the FB pin. A > 10-mil width trace is recommended for heat dissipation. Connect a separate VOUT trace to the upper feedback resistor. Place the voltage feedback loop away from the high-voltage switching trace. The voltage feedback loop preferably has ground shield.

• Place the SS capacitor and RT resistor close to the IC and routed with minimal lengths of trace. A > 10-mil width trace is recommended for heat dissipation.” [8]

The mentioned measures above from the data sheet were met in the final layout of all buck converters as well as possible. The data sheet offers an example layout as shown in figure 29. For a clearer overview for the following statements, it is recommended to open the PCB document in the appendix 5 with Altium Designer or to take a look at figure 20 and 21 from the previous chapters, to understand which line in figure 30 is what. Important to mention is also the numeration of the components in figure 29 and 30 is not the same!

The most noticeable differences from the example layout to the current layout are the VIN and GND traces. They are significantly broader in the example. Additionally, the example design has much more vias. According to the internal experts at FHGR, these designs are oversized and idealised, which is why these specifications were not adopted one-to-one.

Another part that has also not been complied with was that the lines of the voltage feedback loop of the resistors R3, R4 and R5, shown in figure 30, have no ground shield.

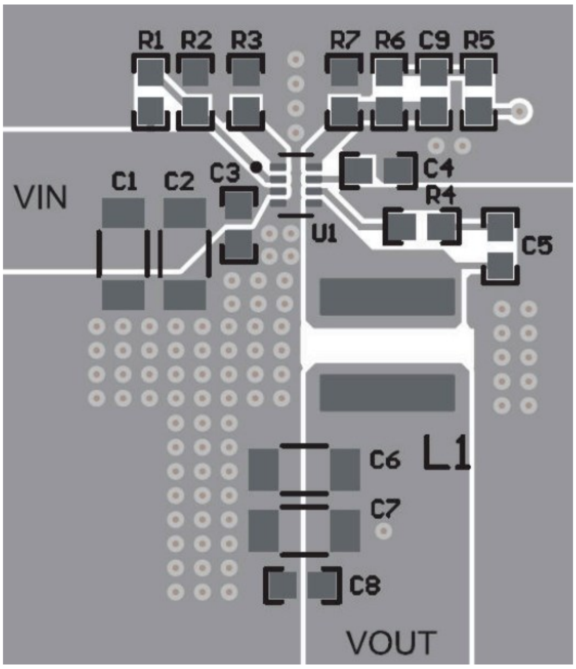

Figure 29: Buck Converter Layout Data Sheet [Own Illustration]

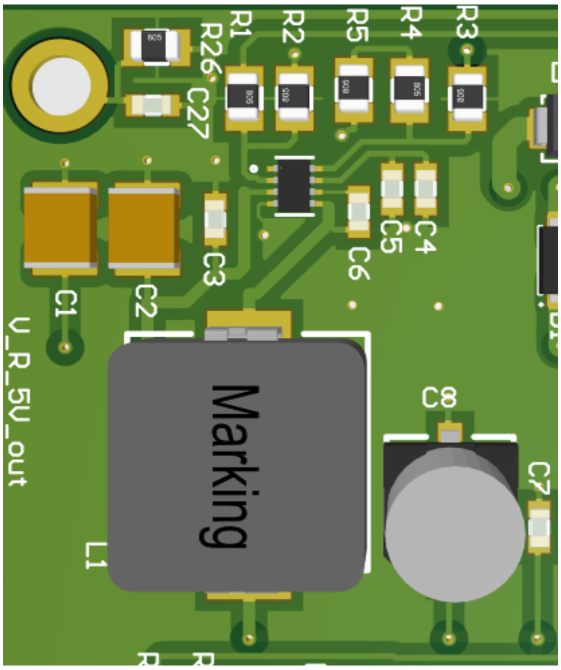

Figure 30: 5 Volt Buck Converter Layout [Own Illustration]

4.10 Assembly of the Electric Interface

To make the production of the electrical interface more economical, a stencil for equipping the PCB with the help of a reflow oven was ordered.

The following instructions show the ideal procedure for equipping the PCB.

The PCB must be perfectly aligned with the holes of the stencil as shown in figure 31.

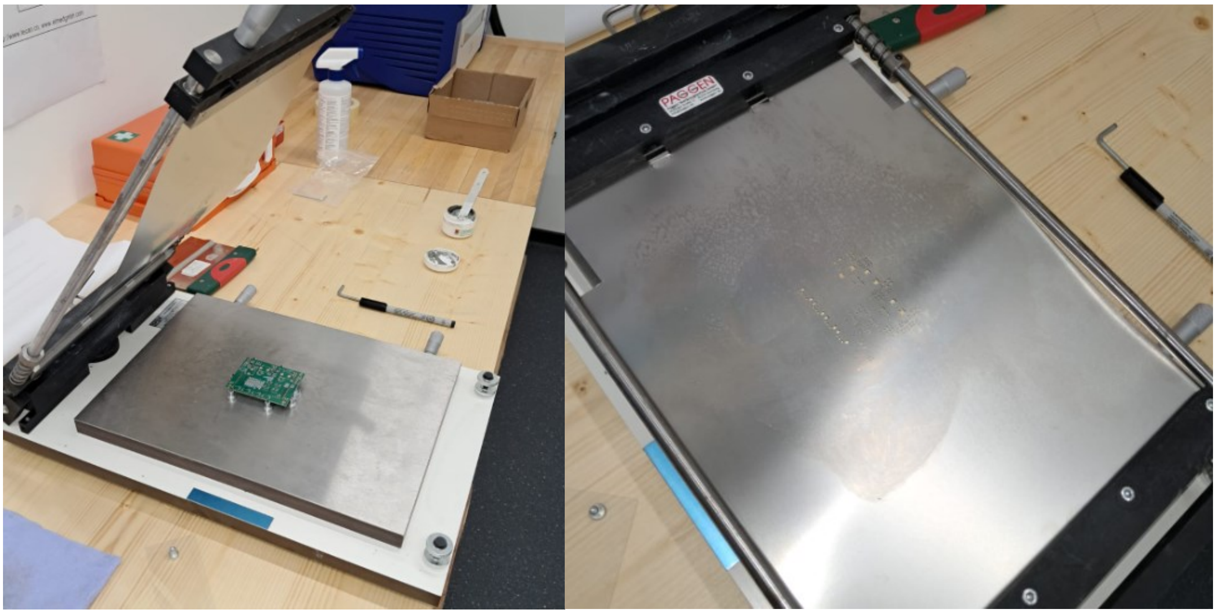

Figure 31: Stencil with Holder [Own Illustration]

Solder paste was then applied to the PCB using a scraper and the stencil, as shown in figure 32.

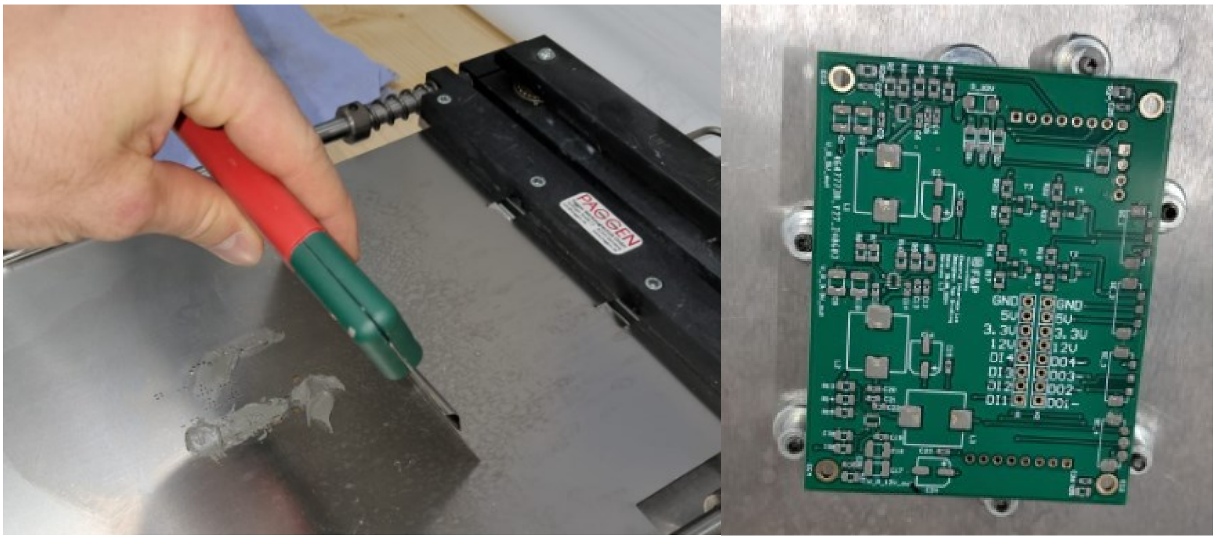

Figure 32: Applied Solder Paste on PCB [Own Illustration]

Afterwards most of the components were placed on the PCB and held in place due to the sticky characteristics of the solder paste. Components on the underside of the board and through-hole-technology (THT) parts were soldered afterwards by hand.

The whole board was then placed in a preheated reflow oven and a preset program with a cooling process was run to solder the parts onto the board. Nevertheless, it was crucial to check the solder connections, especially around the buck converters due to their small size.

Finally, the stencil was cleaned so that it could be used in the next application and the holes would not be clogged with previously dried solder paste.

The final board can be seen in the figure 33.

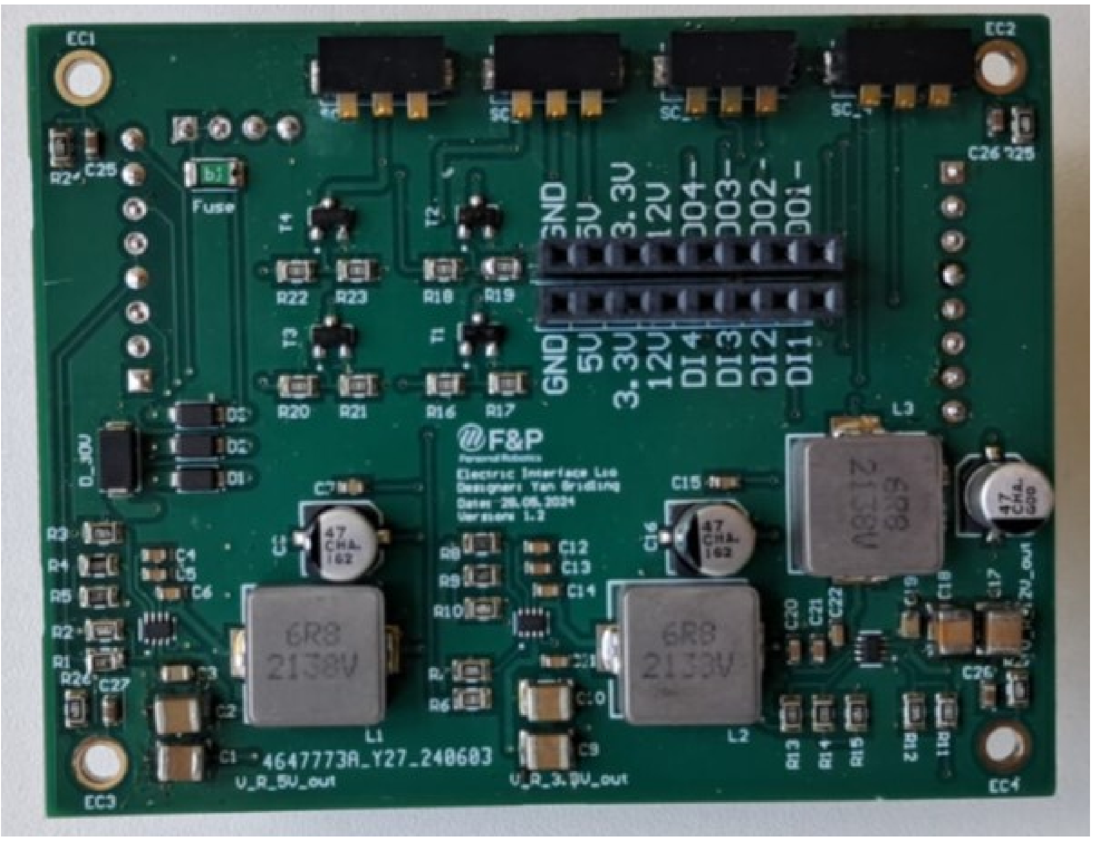

Figure 33: Finished Print [Own Illustration]

4.11 Results Electric Interface

The following chapter summarises the measured results of the electrical interface on the topics EMC, efficiency, the effective output ripple voltage and ESD.

4.11.1 EMC Emission

Lio has not yet been tested for EMC standards and therefore does not specify which standards the electrical interface must comply with. Nevertheless, it will be tested according to general standards.

Hence, the general standards are EN 61000-6-3 CISPR 32 Class B for conducted and radiated emissions and to EN 61000-4-3 for immunity, both of which can be found in appendix 9.

Class B is for residential and commercial areas and has higher demands on standards when considering only the emissions. This makes sense, since Lio is used in nursing homes and residential areas, hence the emissions should be as low as possible. On the other hand, EN 61000-4-3 is for industrial areas and has higher demands in terms of immunity.

This means that the electrical interface is tested for the more stringent standards to comply with in each case.

The build-up figures and further information for the following tests can be found in the file "EMV Praesentation_FHGR_2023" in the appendix 9 or in [9].

4.11.1.1 Average Peak and Quasi-Peak

The figures in the following captions describe values such as average, peak and quasi-peak. Measurements are taken for each frequency over a certain period of time. The average value is, as the name suggests, the average value of the amplitudes over this time. As expected, signal peaks are the highest points of a signal.

The definition of the quasi-peak is more complicated. It is important to note for further understanding, that the quasi-peak is always between the peak and the average value and is a measure that represents the strength and occurrence of the peaks.

The detection of the quasi peak is shown in figure 34 and is used to compute the effective quasi peak.

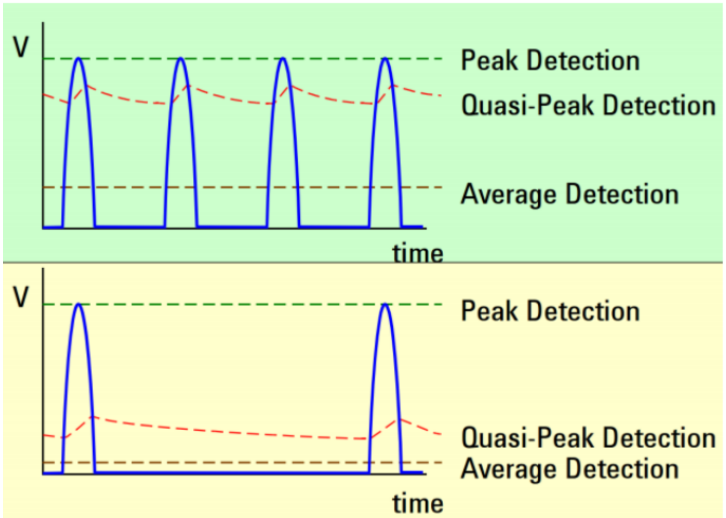

Figure 34: Average Peak and Quasi Peak [9]

4.11.1.2 Conducted Emission

The test for conducted emission demands that the device is connected to the power supply with an 80cm long cable and that it has a vertical distance of 40cm to a reference mass. Shown in figure 35, the electric interface with certain consumers is on the left side with the power supply, not visible, on the right side and the reference mass as the vertical copper plate at the top of the figure.

The emission level of the line at frequencies from 150kHz – 30MHz was then recorded and checked to ensure that certain limits were not exceeded

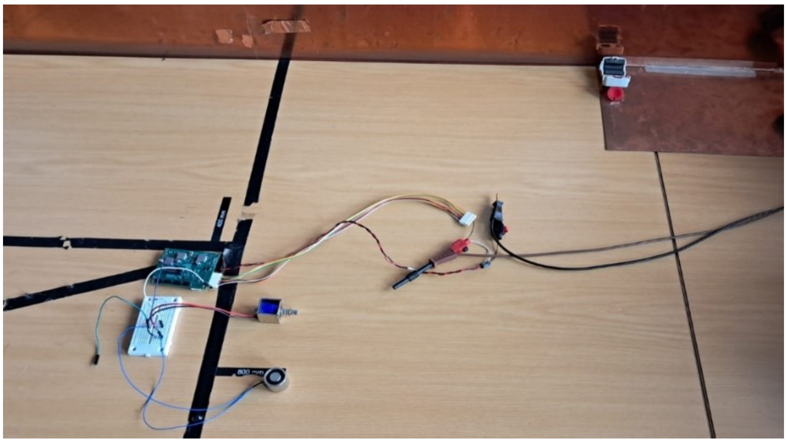

Figure 35: Conducted Emission Test Build-Up [Own Illustration]

4.11.1.2.1 24VDC Supply Buck Converter 3.3, 5 and 12 Volts enabled

In figure 36, the horizontal axis describes the frequencies and the vertical axis the amplitude in dBµV of the emitted waves.

The blue line is the average limit, which must not be exceeded by any of the blue waves in order to meet the Class B standard. The red line is the quasi-peak limit of the waves emitted and must not be exceeded by the red waves.

It is easy to recognise that the standards are met if all the converters are switched on without any electrical load.

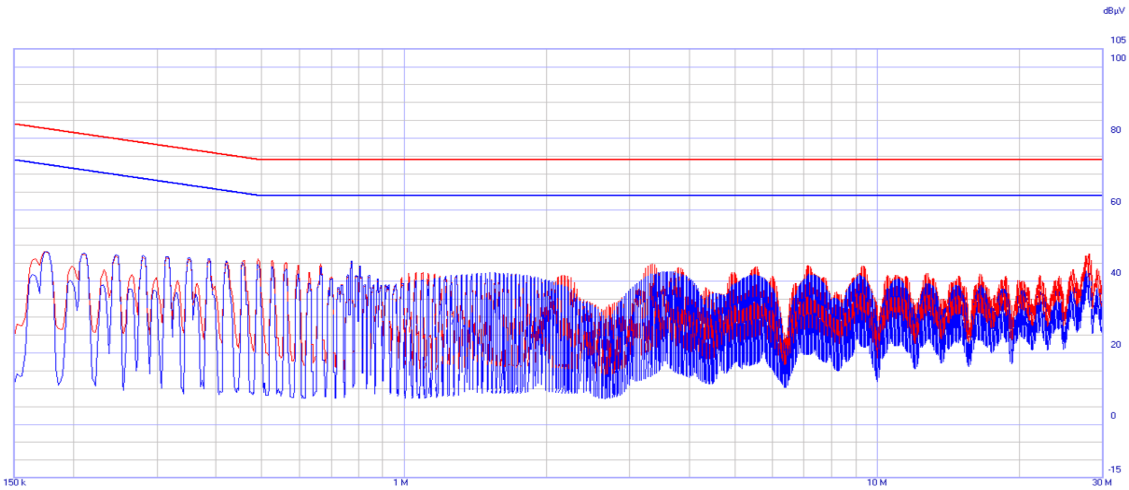

Figure 36: All Buck Converters enabled [Own Illustration]

4.11.1.2.2 24VDC 5Volt Buck Converter under full load

When a buck converter is under full load with three amperes, class B is not reached as shown in figure 37.

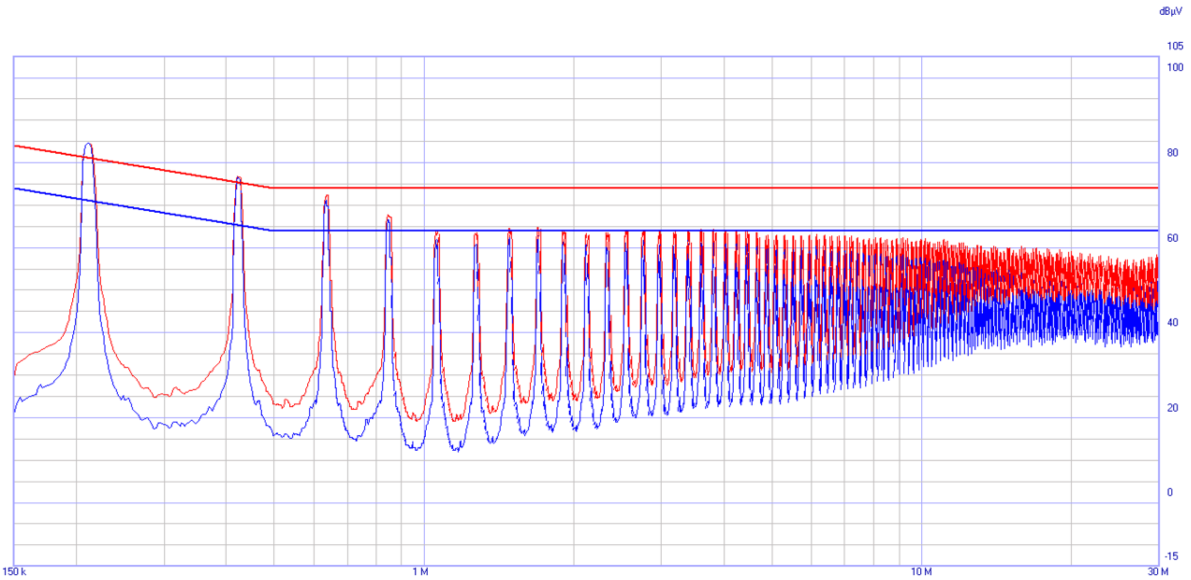

Figure 37: 5 Volts Buck Converter Full Load [Own Illustration]

4.11.1.2.3 Opportunities for Improvement

One way to improve this condition is by using capacitors with greater capacity at the input of the buck converter, around an additional 10µF. As shown in figure 38, the limits are not exceeded. Nevertheless, this solution is not sufficient if the other two buck converters have loads above two amperes.

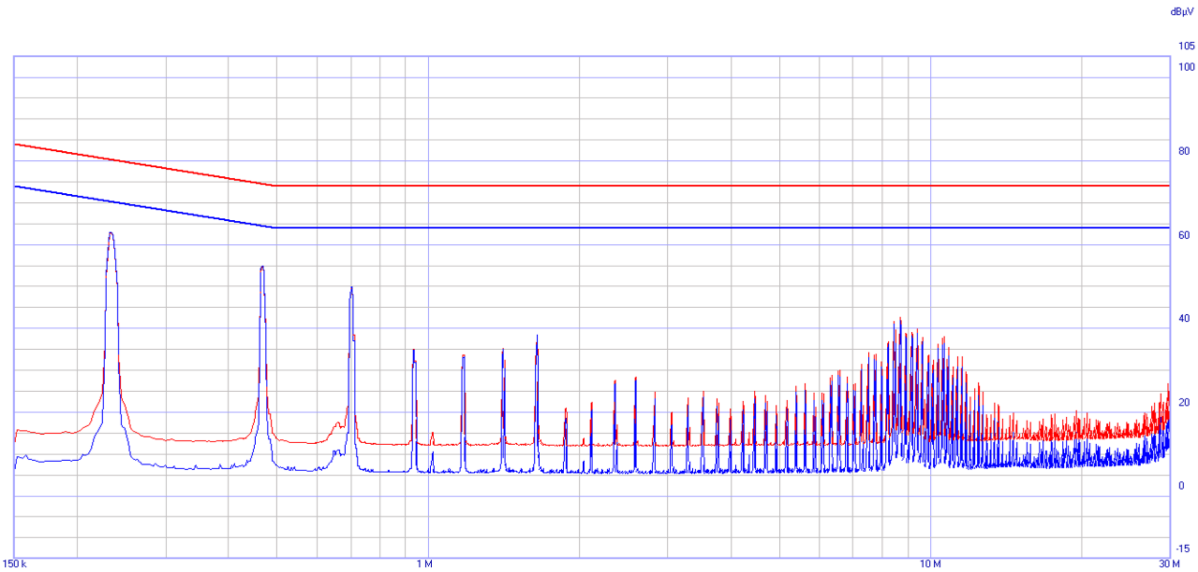

Figure 38: 5 Volts Converter full Load with bigger Capacitors [Own Illustration]

A far better approach is to use a common mode choke which works as a filter. A common mode choke is a special kind of inductor which is used to suppress common mode noise in electronic circuits. The choke consists of a core material (often ferrite) and two or more windings wrapped around the same core. It is important to note that a part of the electromagnetic waves will be converted into heat, thereby reducing the emission [10].

The choke is connected in series with the supply cable. In figure 39, the system was nearly pushed to its limit. Each buck converter had a load of 2.5 amperes, and with the help of the choke, class B was reached. The choke was from the company Würth Electronics with the component number 7448050219 and has an inductance of 190mH.

Further measurement in terms of conducted emission are not documented in this paper. The 190mH choke was the largest internal coil of the FHGR that could withstand the corresponding load. By measuring chokes with different inductance values, it was observed that the pattern was the same, the greater the inductance, the lower the emissions. Hence, if F&P wants to comply with the class B standards, the implementation of a coil of around 200mH is the easiest solution. The electric interface does not have a choke in the current version.

Figure 39: Each Converter 2.5A Load Suppressed with Choke [Own Illustration]

4.11.1.3 Radiated Emission

The test for radiated emission demands that the device is placed 80cm above the ground and has a horizontal distance of 3m to 10m from a broadband antenna as shown in figure 40.

The test specimen is then tested for emission frequencies from 30MHz to 6GHz.

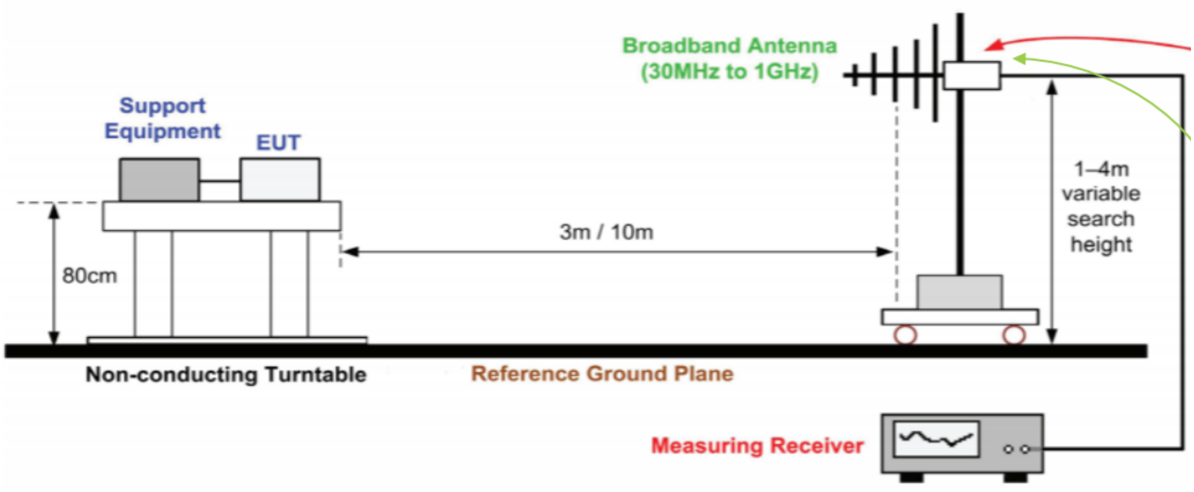

Figure 40: Radiated Emission Setup [9]

4.11.1.3.1 Full Load of System without Measures

The axis of the graph has the same scale units as the conducted emission graphs. However, the blue horizontal line is the quasi-peak limit of class A and the red horizontal line for class B. The green waves in the figure are the effective measurements of the peaks at a certain frequency. The red waves are again the quasi-peak detection and only occur where the peak values are nearly at the class B limits. Hence, for the radiated emission standard only the quasi-peak measurement is important.

Figure 41 shows the blunt system with full load, thus each buck converter is driving a current of nearly three amperes. The measurement was disrupted because the class B limit was already exceeded.

Figure 41: Radiated Emission System Full Load [Own Illustration]

4.11.1.3.2 Full Load of System with Ferrit on Power Supply Entry

As described in 4.11.1.2.3, a ferrite choke was put in series with the power supply of the electric interface. In figure 42, the quasi-peak measurement does not exceed the class B limit, thus the standard can be fulfilled with the same solution as for the conducted emission.

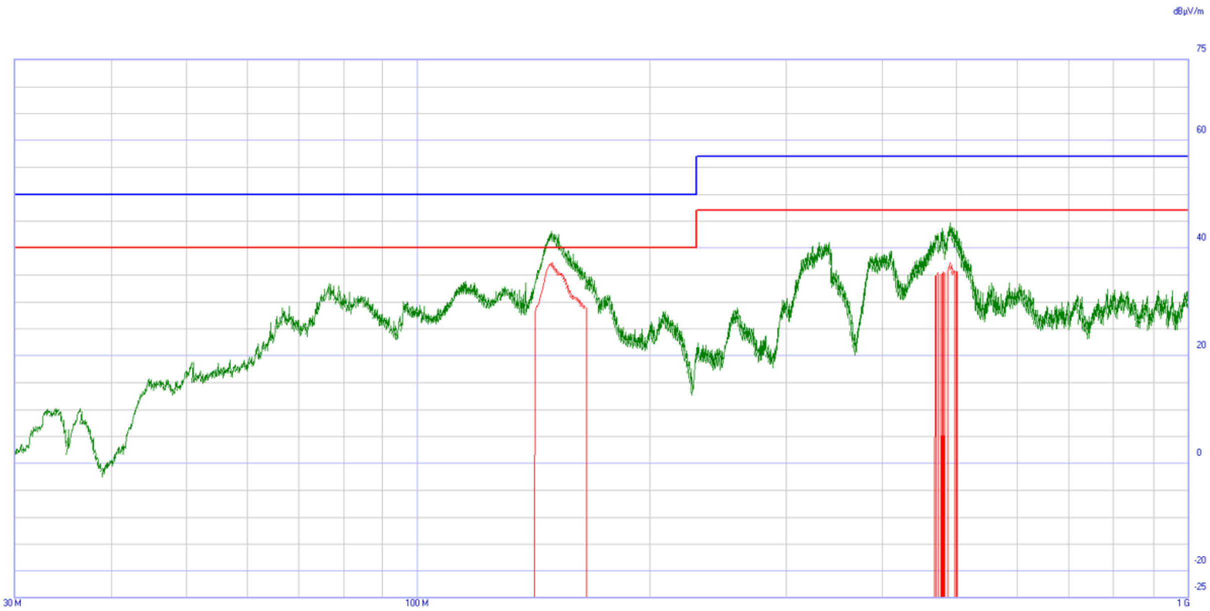

Figure 42: System Full Load with Ferrit on Power Supply Entry [Own Illustration]

4.11.2 EMC Absorption

To conduct the testing for the industrial immunity standard 61000-4-3, the setup was the same as for the radiated emission. The only difference was that the antenna did not work as a receiver but acted as a transmitter by emitting an electric field.

The system was exposed to the frequencies of 80Mhz-1000MHz with an electric field strength of 10V/m. To ensure that the system operated during this whole testing process, the electromagnet was switched on and a metal plate was placed so that it would fall to the ground if a system failure occurred.

There was no system failure during the entire test period, and it can be assumed that the industrial immunity test was fulfilled. Nevertheless, this test is of course very amateurish, but the electrical interface offers no other possibility to record values as it has no logic on board. In addition, the test condition is also a worst-case scenario, as Lio will probably never operate in an industrial zone.

4.11.2.1 Efficiency

The TPS62933ODRLR has a nonswitching quiescent current of around 50µA [8]. The measurements of the efficiency of the buck converter will begin with output currents of around 1mA, to have a good comparison with the data sheet.

Figure 43 shows only efficiency values of up to two amperes to prevent overloading of the power resistors used for the measurements. In addition, figure 43 serves only as a comparison to figure 44, to check that the effective conversion of the voltage transformer also delivers approximately the expected values up to two amperes. With this comparison, it can also be assumed that the heat development of the buck converter is as presented in the data sheet and is therefore not documented further.

Considering possible measurement errors of the measurement chain, it can be said with confidence that the results are within the expected range and are therefore satisfactory.

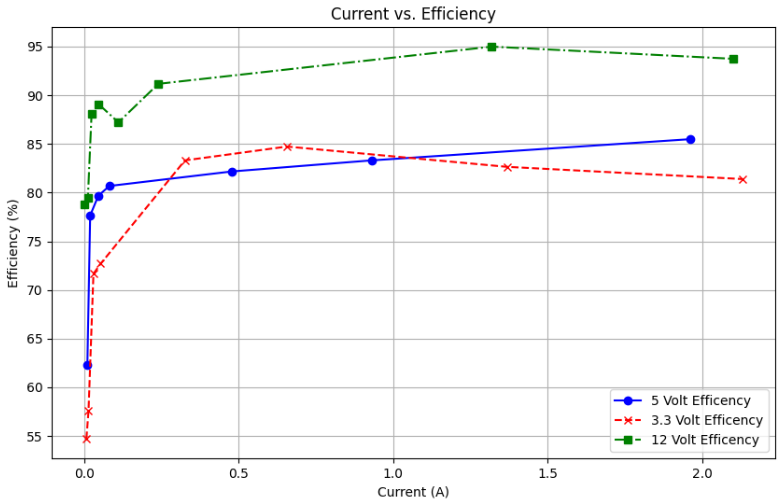

Figure 43: Efficiency Curved Measured Buck Converter [Own Illustration]

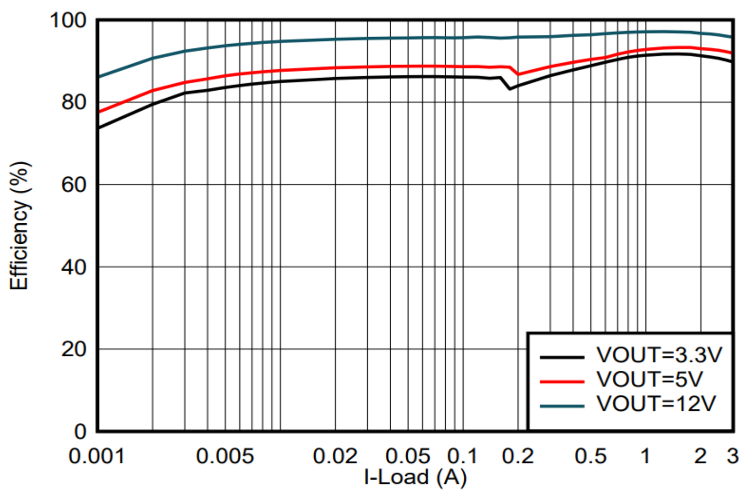

Figure 44: Efficiency Curved Data Sheet Buck Converter [Own Illustration]

4.11.2.2 Output Ripple Voltage

As computed with formula 3 and 4, the maximum peak to peak ripple voltage will converge to the limit value of around 120mV when reaching the maximum output current of three amperes, as seen in the 3.3 and 5 volts graphs.

These values are also satisfactory, considering that it is even possible to power a Raspberry Pi with a maximum input voltage range of 5%, hence 4.75-5.25 volts [11]. These limits are undercut by far, due to the fact that the average power consumption of the Raspberry Pi is about one ampere and figure 45 shows that the ripple voltage is only about 40mV [12].

The reason why the ripple of the 12 volts voltage supply is significantly less than of 3.3 and 5 volts can be explained by looking at formula 3 and 4. The switching frequency of the 12 volts converter is not 500kHZ but 1.2MHz. Hence, the division with the higher frequency decreases the computed ripple value significantly.

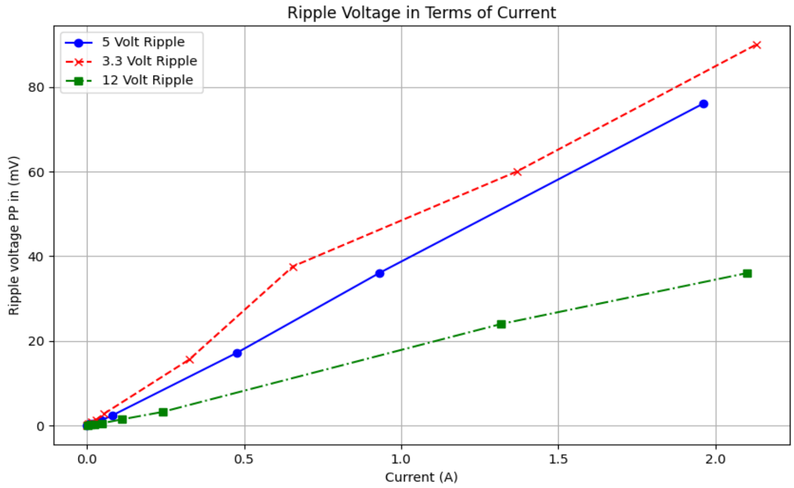

Figure 45: Ripple Voltage in Terms of Output Current [Own Illustration]

4.11.3 ESD

All open contact points of the electrical interface were tested with the ESD gun, which is shown in figure 46, for voltages of up to 8000 volts air discharge and 4000 volts contact discharge. During this entire time, all voltage transformers were switched on. The results showed that the system withstood all impulses without any problems. Standards for residential areas are fulfilled and further measures such as a metal housing or ESD warning stickers are not necessary.

Figure 46: ESD Test [Own Illustration]

5 Mechanical Build

5.1 Overview

The first chapter of the mechanical build only deals with the structure itself and the idea behind it. The following chapter describes how everything is assembled and mounted.

Everything was designed in Fusion 360 and printed with the internal 3D printers of the FHGR. The STL and G-code files to manufacture the parts can be found in appendix 10.

As already mentioned in the task description, the main objective is for Lio to dock to a laundry cart with the help of an additional Add-On mechanism via a docking part which is fixed mounted on the cart, as shown in figure 47.

Important to mention is, that the electromagnet was removed from the final design. Tests showed that the pulling force of the electromagnet was far too weak to pull the cart to the hooking mechanism. Other magnets were not ordered as the docking process worked fine with just the camera and the hook itself, as will be seen later.

Figure 47: Overview System [Own Illustration]

5.2 Structure Mechanical Build

All parts of the mechanical build have hollow cable channels inside to hide the cables which are used for the electronic components, as it will be seen later on.

5.2.1 Distance Bow

To reach behind Lio, a bow was constructed and mounted on the Add-On support plate as shown in figure 48.

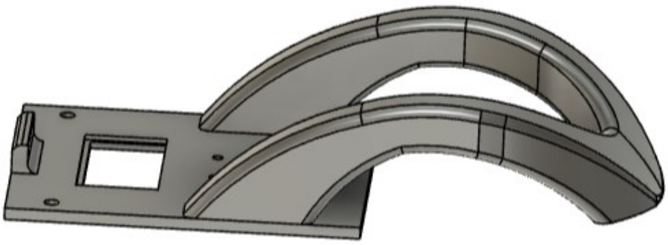

Figure 48: Distance Bow [Own Illustration]

5.2.2 Connection Bolt and moveable Lever

To guarantee that the hooking mechanism is rotatable, a plain bearing in the form of a two-part connecting bolt was manufactured to hold the docking mechanism, as shown in figure 49.

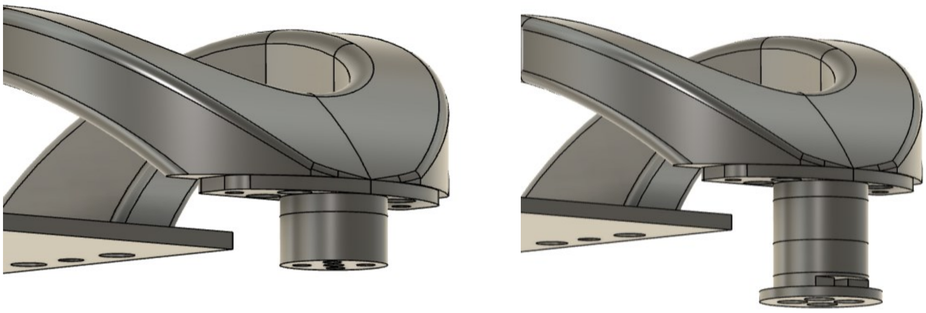

Figure 49: Connection Bolt [Own Illustration]

5.2.3 Lever

The rotatable lever part has various recesses and is hollow so that a movable slide and all actuators can be installed in it, roughly recognizable in figure 50. To guarantee that the lever is always aligned backward, two rubber parts were mounted left and right of the bearing point.

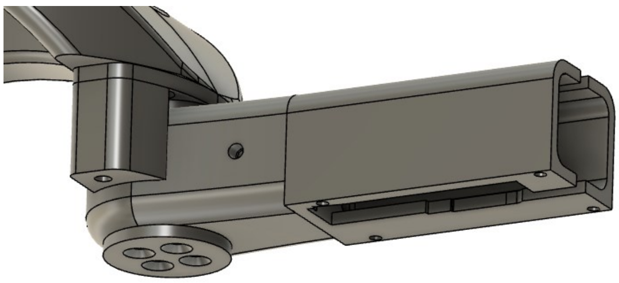

Figure 50: Lever [Own Illustration]

5.2.4 Slider Part

As mentioned above, inside the lever is a movable slide. The slide is held in place with a pulling spring which will get clearer in the following assembly part. The hook and the linear switch are mounted onto this slide, as shown in figure 51. The hook can also be rotated and is pivot-mounted with a pin. The linear switch presses against the backside of the hook, causing it to rotate upwards. What is not visible is that the hook is still held in place by a torsion spring. Also, very important on the slide is the protrusion indicated by the red arrow. When the slide is pulled out to a certain distance, this protrusion presses on a push button.

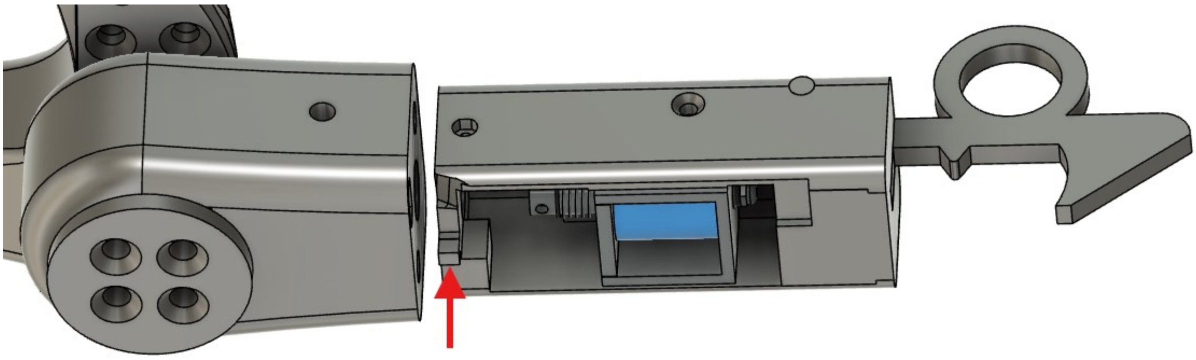

Figure 51: Slider Part [Own Illustration]

5.2.5 Lid

To close the recesses of the lever part, a lid was designed that also holds the pushbutton, as shown in figure 52.

Figure 52: Lid [Own Illustration]

As mentioned, if the slide is pulled to a certain distance, it will push the pushbutton, as shown in figure 53.

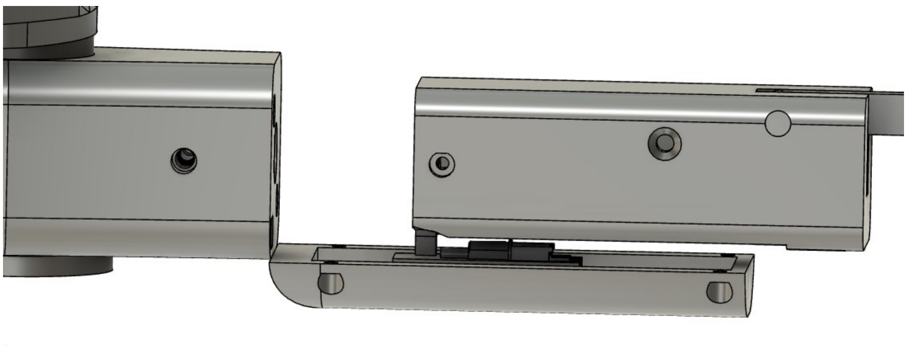

Figure 53: Pushbutton and Sled Interaction [Own Illustration]

Finally, after the lid has closed everything, the hooking mechanism appears as shown in figure 54.

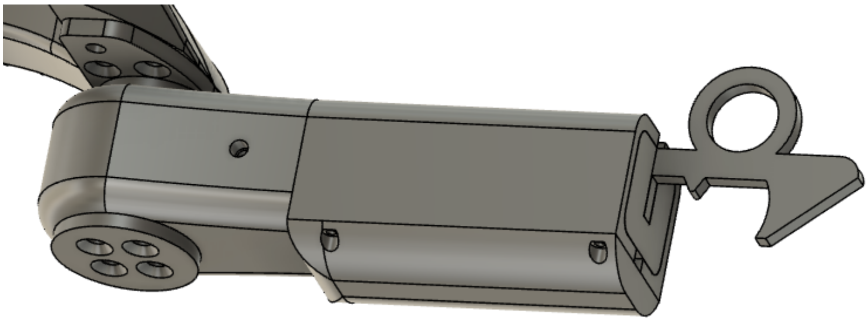

Figure 54: Hooking Mechanism Closed [Own Illustration]

5.2.6 Hook Design and Interaction with Docking Part

The hook has a 45-degree edge which is pushed upwards when it presses against the horizontal pin of the docking part and engages automatically when driven far enough.

The docking part shown on the right of figure 55, is a standardized part for the whole docking process. The only thing that needs to be done to use the cart docking Add-On for other laundry carts is to develop a holder which offers this docking part at a height of 45.5cm above the ground. An example of its usage will be presented in the assembly part.

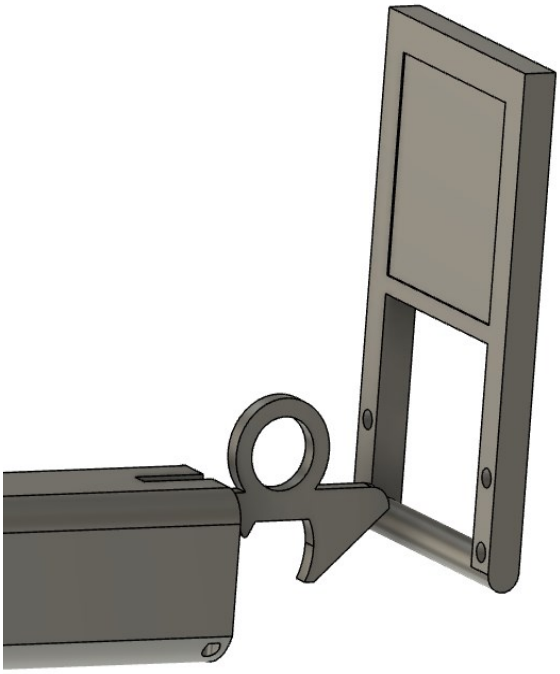

Figure 55: Hook and Docking Part Interaction [Own Illustration]

5.2.7 Spring Counterpart Holder

To hold the spring counterpart in place a two-component attachment was constructed and mounted below the Add-On support plate, as shown in figure 56.

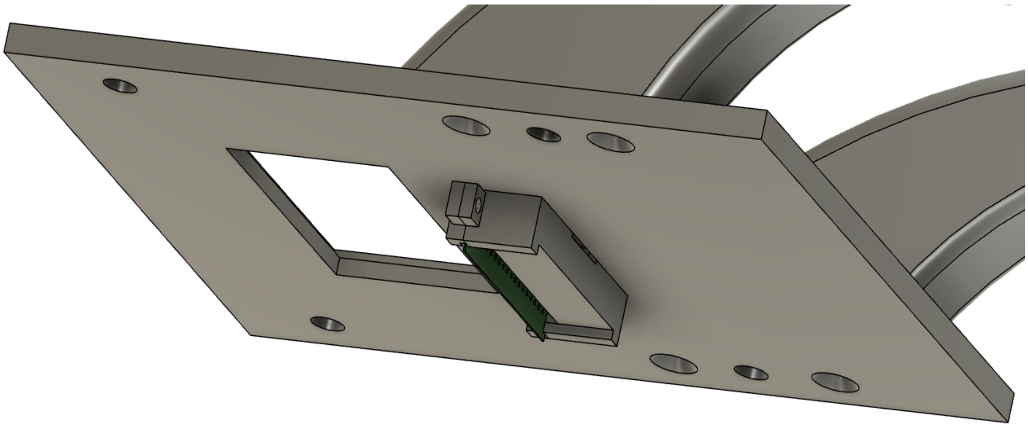

Figure 56: Spring Counter Part Attachment [Own Illustration]

5.2.8 Mounting of Electric Interface

To mount the electric interface, an additional 3D printed part was constructed and mounted on the metal chassis of Lio, highlighted in blue in figure 57.

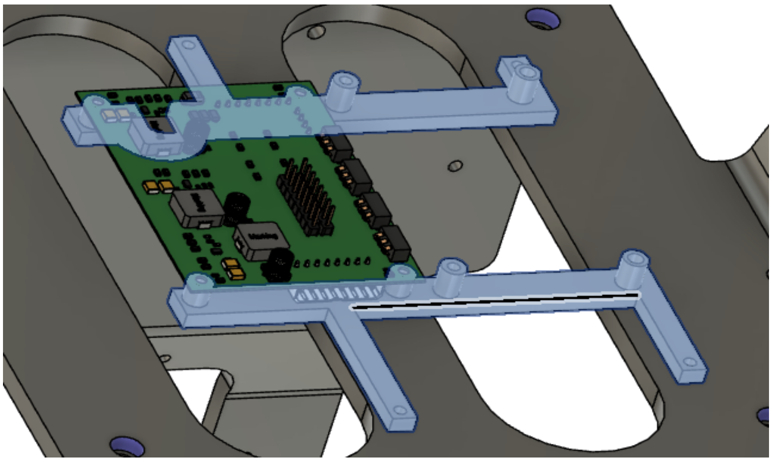

Figure 57: Electric Interface Holder [Own Illustration]

5.3 Assembly

To ensure a smooth installation, the following instructions should be followed in order. The screws required for the next steps are listed in the order file to be found in the appendix 4. If the screws are not described in more detail, they are standard cylinder head bolts.

5.3.1 3D printed Parts

The components have been created with 3D printers. When slicing the parts before they are actually printed, it is important that there is no support material in the hollow areas where the cables will be laid. It is recommended to use the already sliced files provided in appendix 10. The parts must then be freed from the support material.

5.3.2 Preparation of Spring Counterpart

The first step is to prepare the spring counterpart as described in chapter 4.7.3. The cables on the spring counterpart should be around 40cm long and must be litz wire.

5.3.3 Mount Spring Counter Part on Support Plate

The first part is to mount the spring counterpart holder under the support plate with the help of two M2.5*5mm countersunk head screws with corresponding nuts, as shown in figure 58.

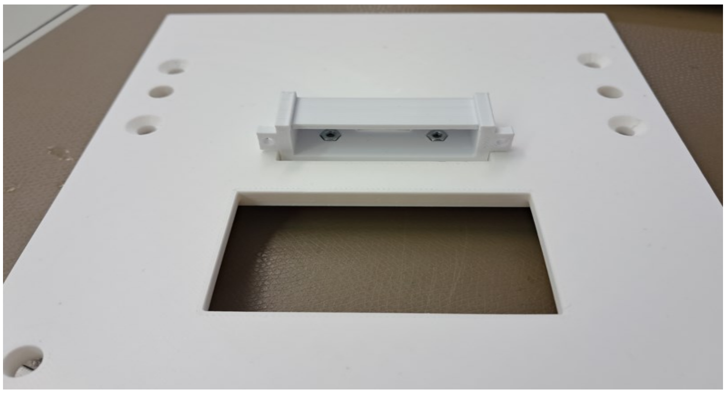

Figure 58: Mounting First Part of Spring Counter Part Holder [Own Illustration]

The second part of the holder is then used to secure the counterpart firmly under the support plate using two M2*14mm screws with two nuts. It is important to insert the cables into the cable duct beforehand so that the final result appears as shown in figure 59.

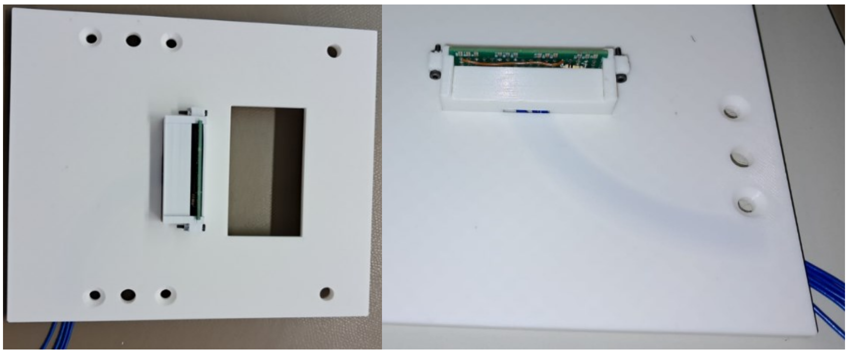

Figure 59: Braced Spring Counter Part [Own Illustration]

5.3.4 Installation of Bow

The following instructions are shown in figure 60.

To mount the bow parts, they first must be equipped with inserts for M5 screws, as seen in the upper left corner. The assembly in this example was made with heated inserts specially designed for 3D printed parts.

The cables can then be guided through the channel of the bow and be screwed to the support plate with two M5*10mm countersunk head screws, as shown in the middle. To guarantee that the two bows are connected cleanly on their contact area, it is recommended to apply some glue on the area, as shown in the lower left part of the figure.

The bows can then be glued together, and the second bow can be screwed to the support plate. The final result of this step is shown in the right part of the figure.

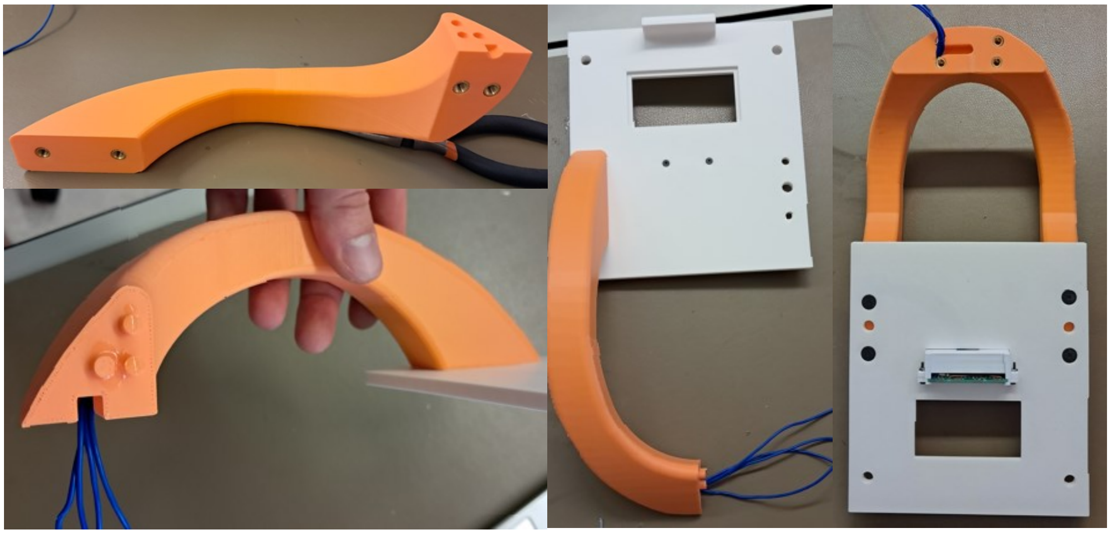

Figure 60: Bow Mounting on Support Plate [Own Illustration]

5.3.5 Preparation of Connection Bolt Part 1

Before the connection bolt, which bears the lever, can be mounted, it must be prepared by inserting four M5 inserts at the top, as shown in figure 61. To avoid a blocking of the inserts due to the melted plastic, it is recommended to recut the thread with a thread cutter.

To limit the range of the lever, two rubber parts are glued and screwed to the connection bolt with M5*40mm countersunk head screws, using nuts and washers.

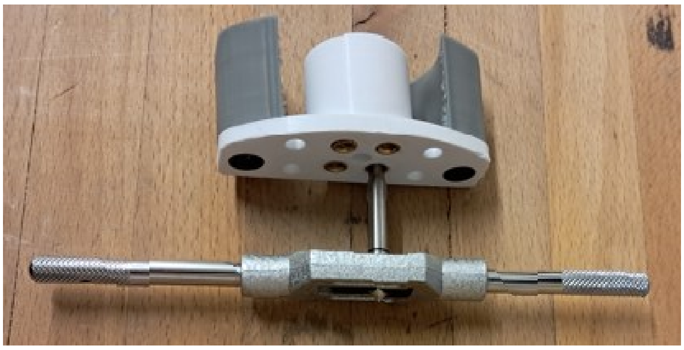

Figure 61: Preparation of Connection Bolt Part 1 [Own Illustration]

5.3.6 Mounting of the Lever to the Connection Bolt

The order of this section is very important! First, the cables need to be guided through the middle hole of the connection bolt part 1, as previously described. Afterwards, the connection bolt part 1 is screwed to the bows with four M5*14mm countersunk head screws.

The cable can then be guided through the lever part and the second connection bolt part, as shown in the left of figure 62.

Finally, the cables are led through the cable channel of the lever and the connection bolt is screwed together with four M5*50mm countersunk head screws. The final result of this step should look like the right part of the figure bellow.

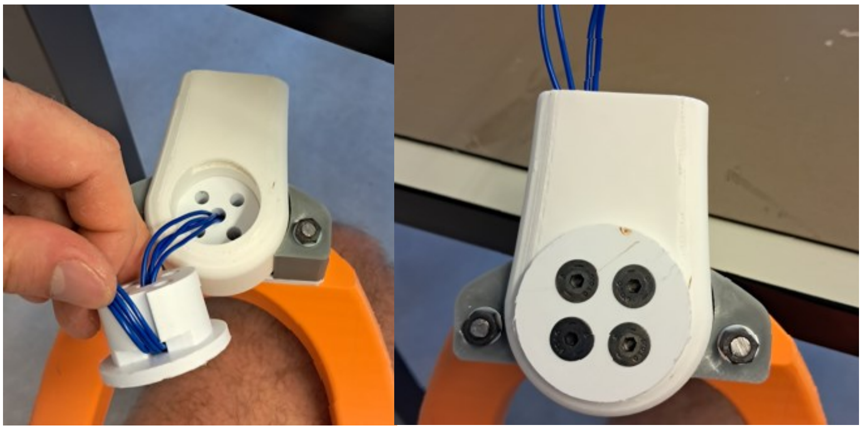

Figure 62: Mounting of Lever to Connection Bolt [Own Illustration]

5.3.7 Connection of Slider Holder to Lever

Before the slider holder can be connected to the lever, the lever needs to be equipped with two M5 inserts, as shown in the left part of figure 63. Additionally, a M2.5 insert must be inserted from the side into the lever part with a M2.5 screw, also shown in the left side of the figure. It is important to try, to unscrew the M2.5 screw again because this screw will later hold the spring in place!

Afterwards, the slider holder can be screwed to the lever with two M5*16mm screws, to be seen in the right part of the figure below.

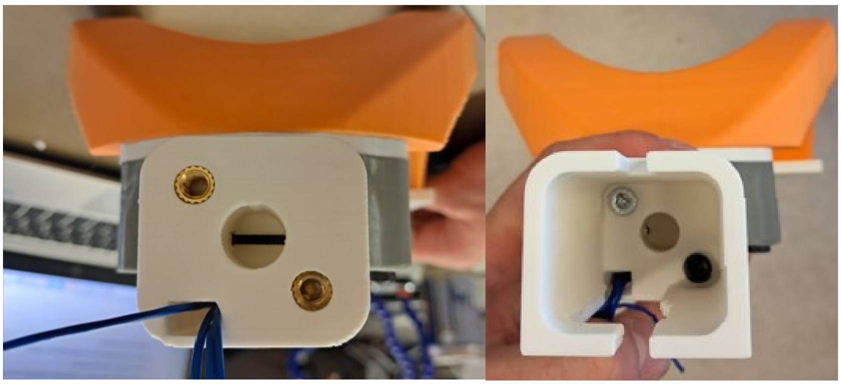

Figure 63: Connection Slider Holder to Lever [Own Illustration]

5.3.8 Preparation of Sled

Both of the following steps can be seen in figure 64. The electromagnetic switch is connected to the sled by using a M3*6mm countersunk head screw. To secure the spring on one side, a bolt or a nail with a diameter of 2mm and a length of 32mm must be passed through the ear of the spring and glued to the sled.

Figure 64: Preparation of Sled Part 1 [Own Illustration]

To pre-tension the hook, a torsion spring was implemented into the mechanism. The torsion spring must be prepared as shown in the left side of figure 65. Afterwards, the torsion spring is pushed inside the opening of the slider, as shown in the middle of the following figure. Finally, the hook can be inserted from above.

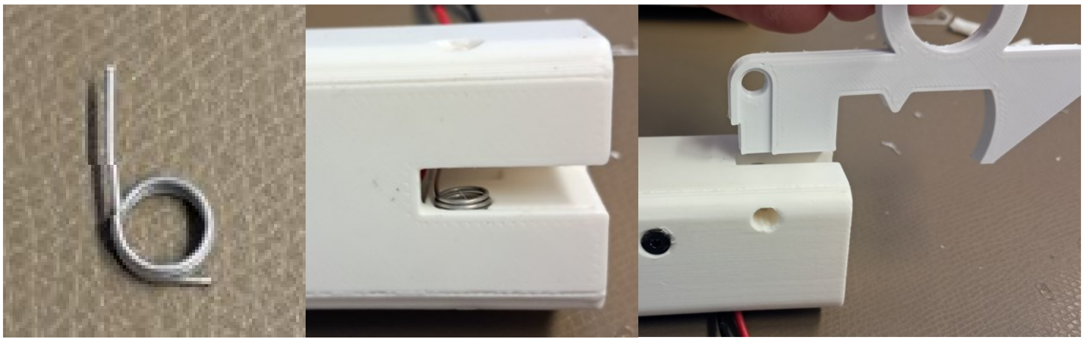

Figure 65: Torsion Spring for Hook [Own Illustration]

Figure 66 shows the process from right to left to secure the hook and to hold him in place. First, a M5*22mm bolt without head is inserted into the hole. Afterwards, a M2.5 insert is inserted into the lower side of the slide. In this insert a M2.5*16mm screw is tightened against the M5 bolt to secure it, as shown on the right side of the figure.

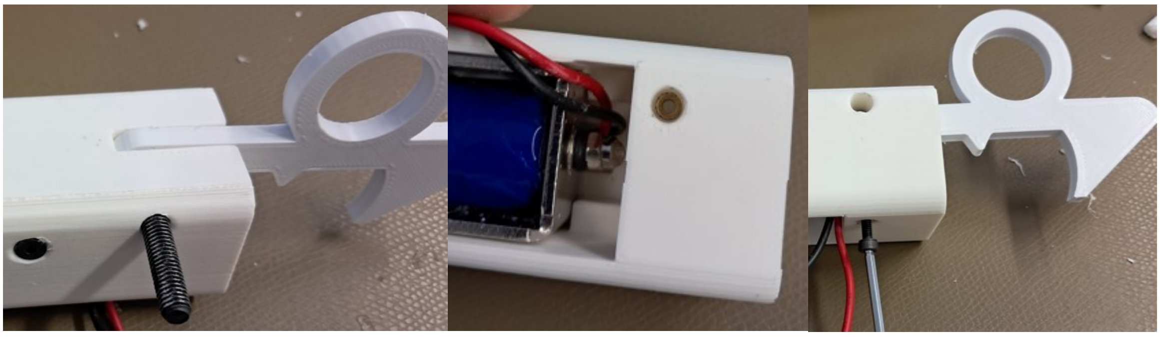

Figure 66: Bolt for Hook [Own Illustration]

5.3.9 Move Sled into Holder

To move the sled into the Holder it is recommended to hold the sled upwards so that the spring is hanging downwards, as depicted in the left side of figure 67. The spring must be led through the hole and the sled must be pushed until it reaches its limit, as shown in the right side of the figure. The screw indicated with the red arrow secures the spring by holding onto the ear of it.

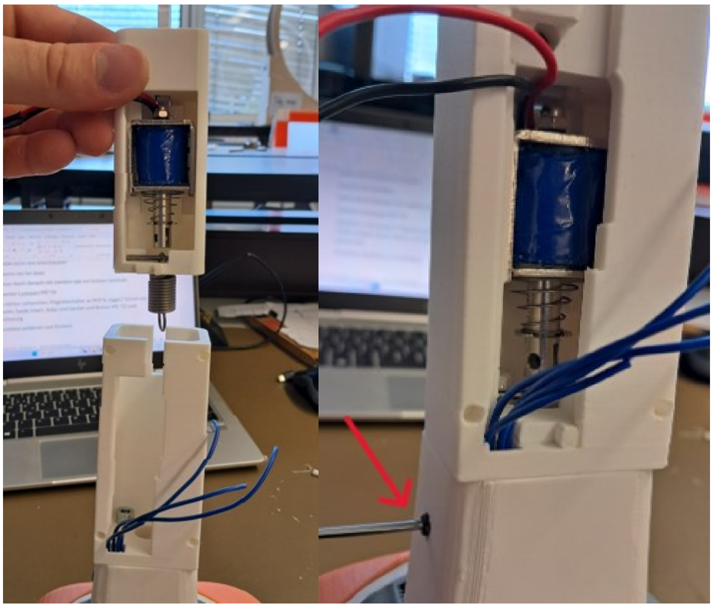

Figure 67: Move Sled into Holder [Own Illustration]

5.3.10 Soldering the Cables and Close the Mechanism

Before soldering the cables, it is important to shorten the cables to around 10cm and to measure which cable is connected with which sliding contact. If litz wires with different colours are available, this step can be skipped. To ensure the correct connections, "5V" is connected with the red cable and the "DO-1" with the black one of the linear switch. One contact of the push button is connected with "12V" and the other with ""DI1". It is important not to forget heat shrink tubing!

The button is then glued to the lid and the cables are distributed, as shown in the right side of figure 68. Before closing everything, four M2.5 inserts need to be inserted into the slider holder, as indicated by the red arrow. Finally, the lid is screwed to the slider holder with four M2.5*8mm screws.

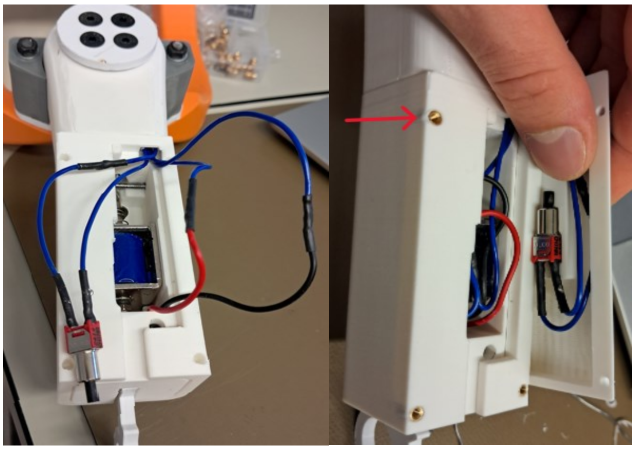

Figure 68: Soldering Cables and Closing Mechanism [Own Illustration]

5.3.11 Finished Add-On Built Overview

The final Add-On should now look like the Add-On in figure 69. The hook should be rotatable but also held in place by the torsion spring. If the hook is pulled horizontally, the sled will be moved outside the slider holder with a maximum range of around 25mm until the push button is pressed.

Figure 69: Finished Add-On [Own Illustration]

5.3.12 Mounting the PCB on Lio

Before mounting the PCB, the back cover of Lio must be removed to expose the metal frame.

To have the PCB at the right height on Lio, the PCB holder, the grey 3D printed part shown in figure 70, must be screwed into the metal chassis of Lio with four M3*15m screws via the already available screw threads of the chassis, as indicated with the red arrows. The shown screws in the corners of the PCB are all M2.5*26m screws. The two screws on the right, as indicated with the green arrows, are mounted with the help of two nuts and washers. To secure the screws indicated by the orange arrows, a thread needs to be cut out into the metal frame with a drill and a thread cutter. To prevent metal shavings from getting inside Lio, it is advisable to briefly remove the metal chassis part beforehand by loosening the screws marked by the white arrows.

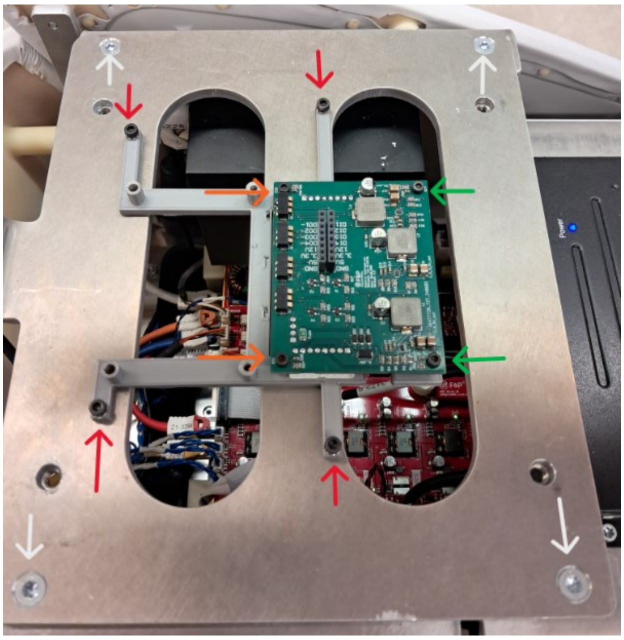

Figure 70: Mounting of the PCB [Own Illustration]

5.3.13 Cable Management

The cables must be prepared as shown in figure 71.

It is important that the connectors are arranged mirrored to each other. This means that the same side of the connector must always face upwards on the opposite side of the cable.

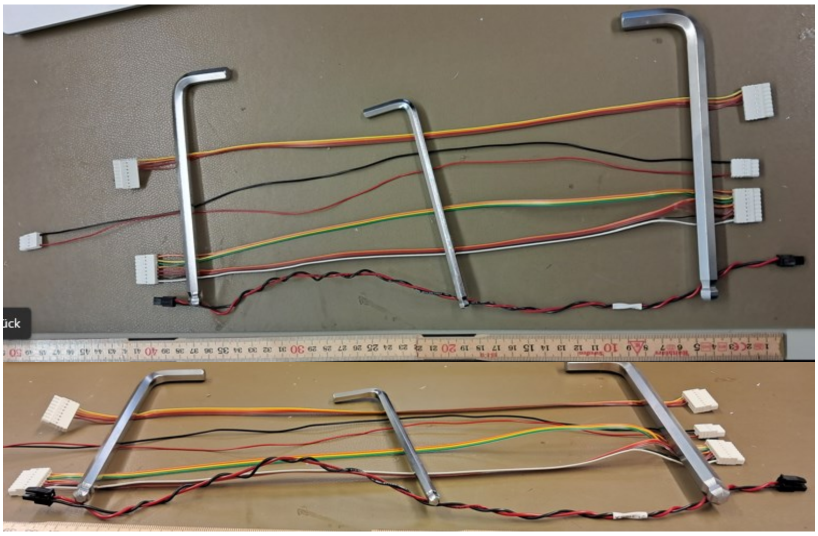

Figure 71: Cable Preparation [Own Illustration]

All cables with their connectors are plugged in as shown in figure 72, beginning from the left with the connection to the P-Rob 3 GPIO interface, followed by the power supply connection to the 18 volts power rail and ending on the right with the connection to the electrical interface itself.

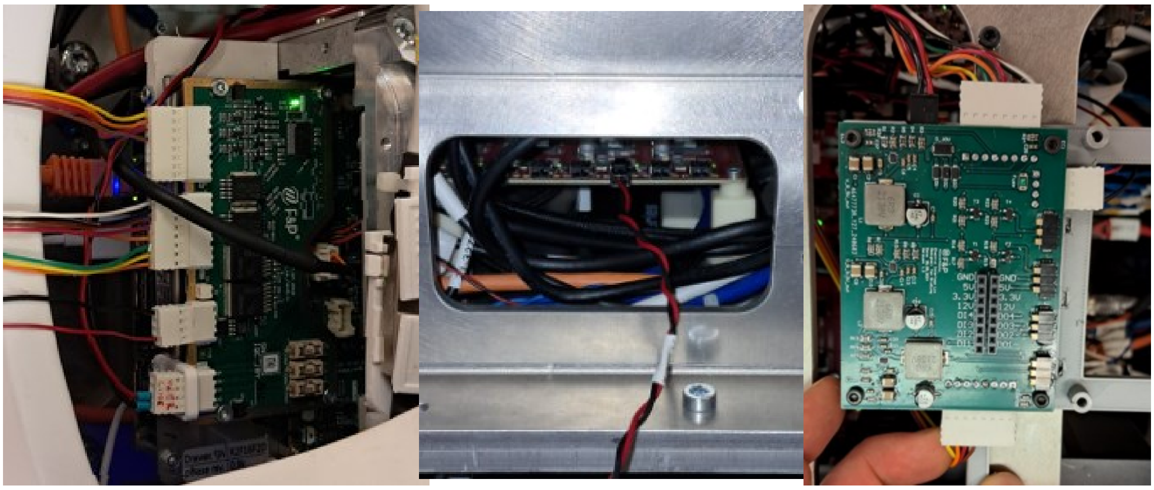

Figure 72: Plug in of Connectors [Own Illustration]

5.3.14 Cutout into Cover

To mount the back cover on Lio again, a cutout with the approximate dimensions as shown in figure 73 has to be made. The cutout does not have to be very accurate since it is later covered by the Add-On interface.

Figure 73: Cutout Back Cover Lio [Own Illustration]

5.3.15 Add-On Interface with Rubber Lid

The Add-On interface is then mounted again on the cover of Lio. To close the hole and to cover the electrical interface, a removable rubber lid was printed with TPU, as shown in figure 74.

Figure 74: Add-On Interface with Rubber Lid [Own Illustration]

5.3.16 Add-On on Add-On Interface

The support plate is equipped with the same opening as the Add-On interface to store the rubber lid when the electrical interface is used by an Add-On, as shown in figure 75.

Figure 75: Add-On mounted on Add-On Interface [Own Illustration]

5.3.17 Example Usage of Docking Part

The mechanical docking process works as described in chapter 5.2.6. Hence, it is important to offer the standardized docking part at a height of 45.5cm. For the example cart shown on the right side of the figure 76, two small plastic parts, shown on the left side, had to be constructed to position the docking part at the right height. Everything is then secured together with four M5*50mm screws along with their corresponding nuts and washers.

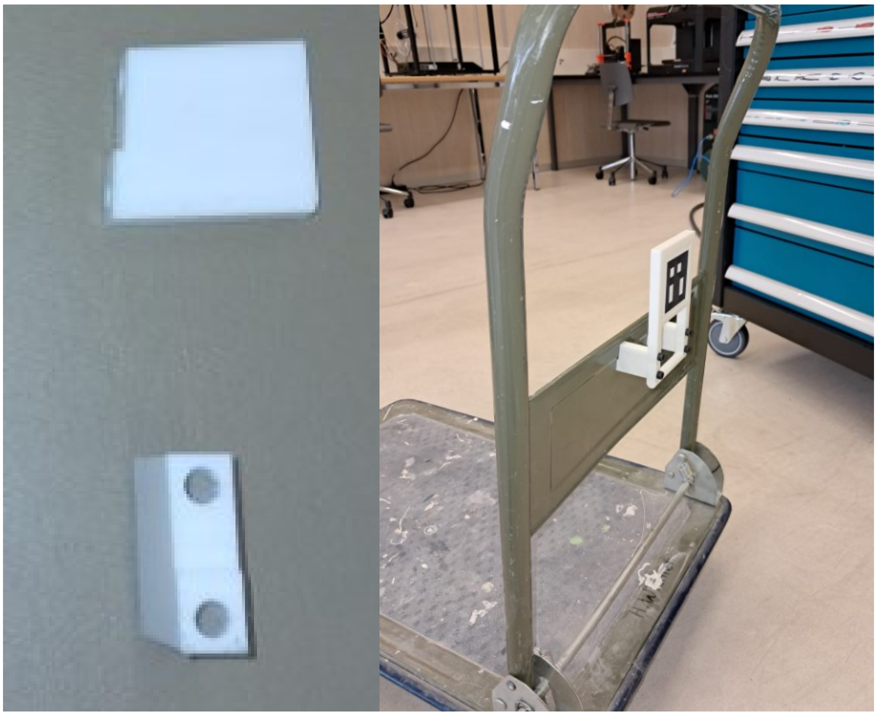

Figure 76: Example Usage of Docking Part [Own Illustration]

5.4 Computation of Torsion Spring for Hook

By converting formula 6 and using the sketch shown in figure 77, it is quickly recognisable that with a weight force F_G of 0.2N for an aluminium hook, a torque M_{TS} of approximately 20Nmm of the torsion spring and the magnetic force F_M of approximately 3N, a positive torque is present even when considering additional friction forces, which are neglected here. This means that the hook would move upwards when the linear switch is actuated.

$$M_{Center} = F_M * 15 - F_G * 45 - M_{TS}$$

Formula 6: Torque Equation Hook

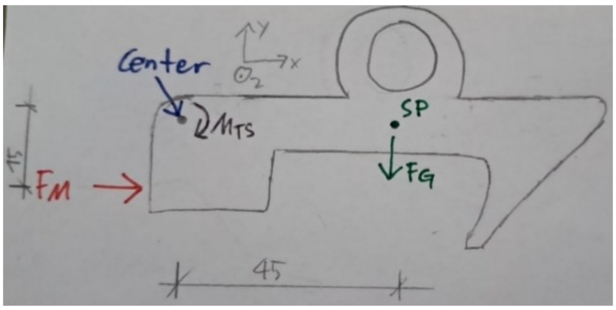

Figure 77: Sketch Computation Torsion Spring [Own Illustration]

5.5 Mechanical Test and Computation of Tension Spring

To determine the maximum tensile force that the mechanism must withstand, a cart was loaded to 60kg. The 60kg is an estimate and reflects the weight of a fully loaded laundry cart, which may even contain wet clothes.

The tensile force was determined using a spring tension scale shown in figure 78. The wheels of the trolley were also rotated to different positions to account for less-than-ideal starting conditions. For 60kg, up to 50N of pulling force is required if the wheels are in an unfavourable position.

To make sure that the mechanism is designed for sufficiently high forces, it was tested with a tensile force of 12kg. This force was withstood without any problems, with even the wheels of the robot starting to spin.

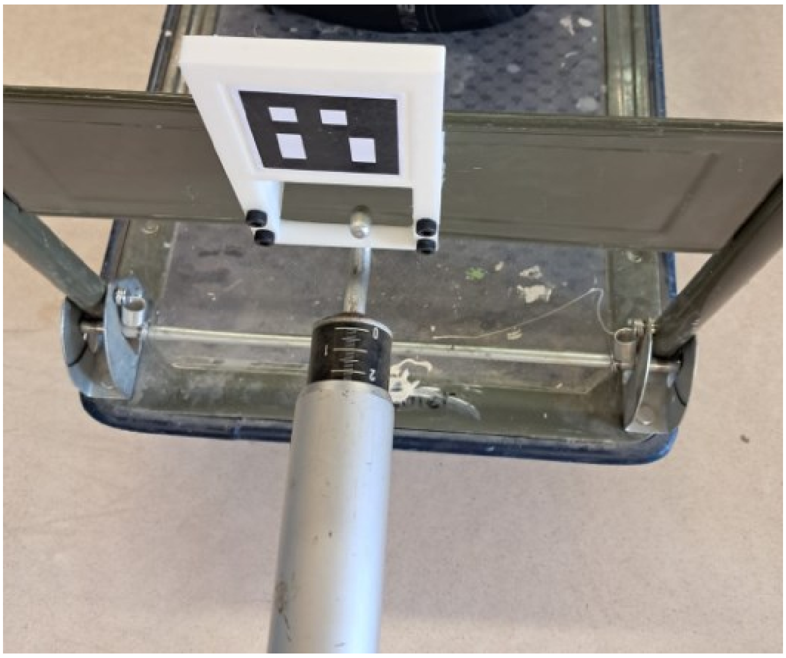

Figure 78: Measuring of Pulling Force [Own Illustration]

To prevent the mechanism from being exposed to such forces in the first place, a tension spring with a pushbutton was installed as already mentioned. With a spring constant value D of 1.885N/mm and a maximum additional extension Δl of the spring of up to 25mm, the maximum force on the mechanism is 47.125N or 4.8kg according to formula 7. After actuating the switch, the mechanism is released via a programme routine.

$$F = \Delta l * D$$

Formula 7: Spring Force

6 Programming for the Docking Process

6.1 myP Overview

MyP is a software framework that gives full access to control the robot as well as to write program applications with the software language Python. MyP offers a large collection of functions to use the robot in a variety of ways. Some of these functions are used to automatically attach Lio to the laundry cart.

A comprehensive documentation of myP can be found in appendix 1.

6.2 Programming Objective

The aim of the entire programming structure for the cart docking routine is to make the entire structure as modular as possible and to work with the provided myP functions.

The executed routines created during this bachelor thesis only serve as an example usage of the created functions and class. This is because there is simply no generally effective implementation that can be used in a wide variety of cases. A finished application varies from customer to customer and is then implemented by F&P itself.

6.3 Documentation Process

To understand how the scripts, functions and even a created class interact with each other, it is recommended to first have a look at the created README file which can be found in appendix 11.

In addition, programme headers and comments sufficiently document the source code of each file. Therefore, the code documentation is not repeated a second time in this report and reference is also made to the appendix.

After gaining a rough overview with the help of the README file, the optimal further procedure to promote understanding will now be presented in the form of instructions in italics.

Open up the myP user manual to quickly look up and understand the used myP functions for the subsequent steps.

Afterwards, open the file "Class_Compute_Navigation_Docking" and read through it. By this point, with the documentation of the two methods "compute_navigation_values" and "compute_starting_navigation", it is advisable to take a look at the following chapter 6.3.1, which visually describes the mathematical processes within these methods.

That followed, the file "functions_execute_docking_laundry_cart" includes the functions for the effective movements of Lio. In addition, "dock_to_cart" shows how these functions are used together.

The file "release cart" is easy to understand without any further context.

Last but not least, "test_movement_interruption_if_laundry_cart_jams" and "check_pulling_force" should be read together and are also very understandable.

6.3.1 Mathematical Implementation of Navigation

6.3.1.1 Normal Docking Process

After the transformations from the camera-detected ArUco marker to the rotational point of Lio were computed, the exact x, y, and z coordinates relative to Lio from the marker are stored in the class attributes. In addition, the turn angle from the ArUco marker to the robot is also stored and is called ey, shown in figure 79 and written in the right upper quarter.

The normal docking process is quite simple to understand with the formulas 8 and 9. The movement is then executed by first turning Lio and then letting him drive in a straight line up to the computed linear distance.

It is important to recognise that a positive turning angle for Lio is by turning counter-clockwise, indicated by the direction of the z-axis!

$$d_{linear} = \sqrt{x_{aruco}^2 + y_{aruco}^2}$$

Formula 8: Linear Driving Distance

$$\propto_{turn} = arctan2(-x_{aruco}, y_{aruco})$$

Formula 9: Turn Angle

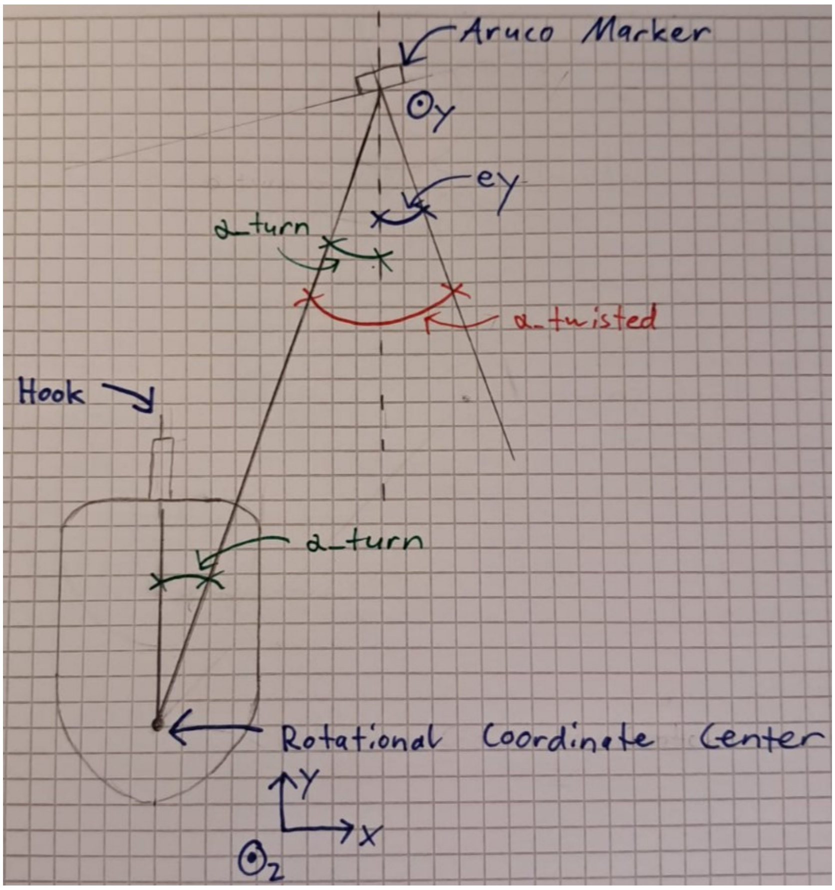

Figure 79: Normal Docking Sketch [Own Illustration]

6.3.1.2 New Alignment

A little more complicated is the determination of when to execute the new alignment routine. The criterion for determining whether Lio needs to realign itself is to calculate how far the robot and the ArUco marker would be rotated from each other if Lio had already rotated.

Formula 10 offers the solution for this issue. Not to forget is the fact, that the angle α_{turn} in the example sketch in figure 79 is a negative angle! Hence, if α_{turn} were not multiplied with -1, $\alpha_{twisted}$ would be far too small.

$$\propto_{twisted} = -\propto_{turn} + ey$$

Formula 10: Twisted Angle of ArUco Marker to Lio

If the absolute value of $\alpha_{twisted}$ exceeds a certain value, as controlled on row 32 in the script "dock_to_cart", Lio will align itself anew.

To determine the new alignment coordinates rectangularly in front of the marker, formula 11 can be used. This formula can be found in the method "compute_starting_navigation" in the script "Class_Compute_Navigation_Values" on row 100 and 101.

$$x_{new} = x_{aruco} + \sin(ey) * d \qquad y_{new} = y_{aruco} - \cos(ex) * d$$

Formula 11: New Alignment Coordinates

The distance d is the attribute "rectangular_distance_to_aruco_new_alignment" and can also be found in the script "Class_Compute_Navigation_Values" on row 34.

The movements to this new starting point, shown in figure 80, are executed like the normal docking process. When this new starting point is reached Lio turns around the angle $\alpha_{twisted}$ so that it is straight in front of the ArUco marker. The mentioned steps are implemented beginning at row 45 in the script "functions_execute_docking_laundry_cart".

Afterwards, the normal docking iteration steps are executed, as implemented in the script "dock_to_cart" after row 33.

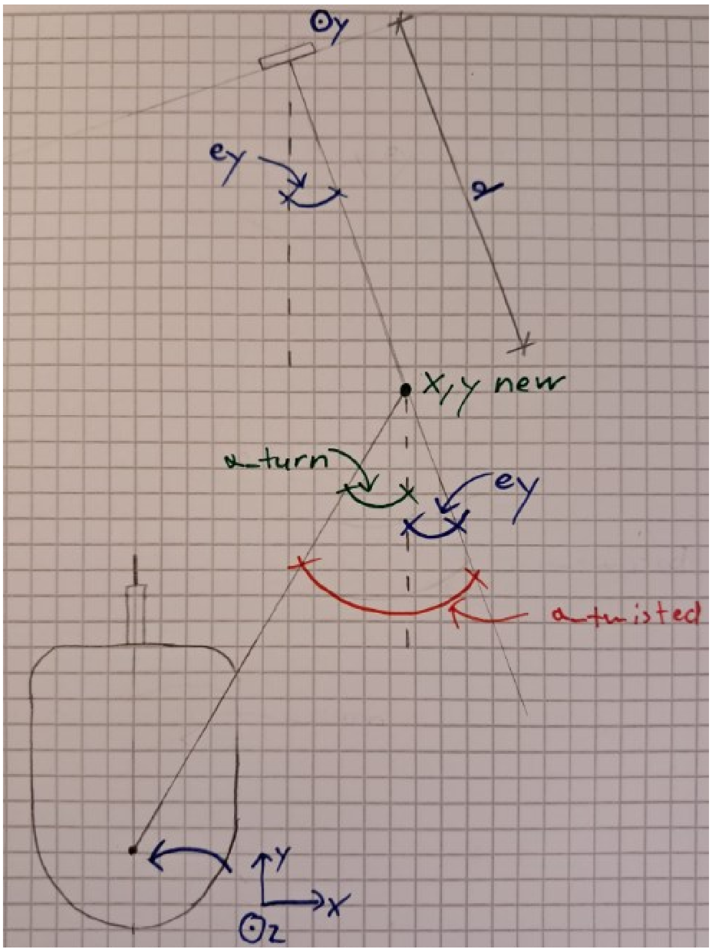

Figure 80: New Alignment Sketch [Own Illustration]

6.4 Failed Approaches

With a comprehensive understanding of the current solution, the failed navigation principles will now be briefly discussed.

6.4.1 Direct Docking

The first solution was to calculate the navigation values in the same way as done in the current solution. Subsequently, the docking process relied solely on Lio's driving commands by turning the robot and then driving the entire linear distance in one piece. Thus, these solutions do not involve an iterative process.

The problem was that the forward movement in particular showed a large drift. By imagining that Lio rotates a bit around its own axis and then wants to drive forwards with the twisted wheels, it becomes clear, that it takes a certain amount of time for the wheels to align themselves to drive in a straight line, and this is exactly what leads to a deviation.

6.4.2 Docking with Parallel Scripts

Another promising approach was to work with the help of parallel scripts. Information on working with parallel scripts can also be found in the myP manual.

The idea was to detect the ArUco marker via the camera using a script running in parallel. In the main script, Lio would then drive in the direction of the marker and receive updates on the relative position to the marker via this parallel script and adjust the course accordingly. Hence, the whole navigation would have been conducted in one smooth driving process without stopping in between.

Unfortunately, the simultaneous detection of the marker with a respective movement of the robot had led to distortions of the image. The reverse transformation and thus the entire docking process became unreliable.

7 Risk Assessment

A risk assessment matrix was created to record various risks and their probability of occurrence for the system, as shown in table 10.

The columns represent the probability of a risk and range from unlikely to certain cases. The rows represent the impact and range from insignificant to catastrophic. The combination of the probability and the impact categorises risks by multiplying the values with each other, whereby values below 6 can be considered as low, from 6-12 as medium and above 12 as high risks.

Probability / Impact	Unlikely	Rare	Possible	Likely	Certain
Insignificant	1	2	3	4	5
Minor	2	4	6	8	10
Medium	3	6	9	12	15
Major	4	8	12	16	20
Catastrophic	5	10	15	20	25

Table 10: Risk Assessment

The corresponding results from the risk matrix are recorded and if needed, each risk is briefly described. Measures implemented to mitigate the risk are then mentioned, if necessary and available. The risk is then assessed again after the measure has been taken.

Important to mention is, that the risk assessment in terms of software is not documented. This is because the topic of error handling was barley dealt with due to the fact that a finished application for a customer is implemented by F&P itself and each application is different from the previous one. Thus, the intention was to avoid restrictions in any way.

However, the modularity of the program structure allows it to be easily extended for these specific applications and error handling.

7.1 Electric Interface Risk Assessment

7.1.1 Short Circuit

Probability: Likely	Impact: Catastrophic	Risk: High

Measures: The voltages accessible for the end user are all short circuit protected by the buck converter itself and limit the current to three amperes.

Probability: Likely	Impact: Insignificant	Risk: Low

7.1.2 Wrong Application of Electrical Connectors

Probability: Possible	Impact: Minor	Risk: Medium

Measures: The connectors should always be mounted mirrored on the cables so that the connectors cannot be connected the wrong way. In addition, the whole electric interface is, as mentioned in chapter 4.3, reverse voltage protected. Hence, if connectors are applied incorrectly, the system would just not work.

Probability: Unlikely	Impact: Minor	Risk: Low

7.1.3 ESD

Probability: Possible	Impact: Major	Risk: Medium

Measures: The electric interface with its components was designed in a ESD-protected way and passed the ESD standards test for living areas.

Probability: Possible	Impact: Insignificant	Risk: Low

7.1.4 Peak Voltages of Voltage Supply

Probability: Unlikely	Impact: Major	Risk: Low

Measures: The electric interface is equipped with a cera diode to handle peak voltages.

Probability: Unlikely	Impact: Insignificant	Risk: Low

7.1.5 Undervoltage of Voltage Supply

Probability: Unlikely	Impact: Major	Risk: Low

The electric interface would just stop working and the desired voltages would no longer be present at the output.

7.1.6 Over-Bending of the spring contacts

Probability: Rare	Impact: Catastrophic	Risk: Medium

Measures: The spring counterpart and its holder for the Add-On support plate were designed with minimum tolerance so that the spring counterpart cannot reach a position to over-bend the springs of the electric interface.

Probability: Unlikely	Impact: Catastrophic	Risk: Low

7.2 Mechanical Build

7.2.1 Overload of Mechanism

Probability: Unlikely	Impact: Major	Risk: Low

Mechanism was tested with more than twice the maximum pulling force and withstood it without any problem.

7.2.2 Person leans against System and breaks it

Probability: Rare	Impact: Catastrophic	Risk: Medium

It is nearly impossible to cover such extreme cases when mostly relying on 3D printed constructions. PLA constructions with the help of inserts are not made to handle high torques.

7.2.3 Rubber Parts do not align the lever back to the Centre Position

Probability: Possible	Impact: Medium	Risk: Medium

Measures: A Person could push the lever back to its centre. Or as described in the chapter 8.5, the lever can be equipped with an ArUco marker, so that Lio can measure how far the lever is twisted away from its centre before the docking process starts and take it into account.

Probability: Possible	Impact: Minor	Risk: Low

7.2.4 Hook breaks

Probability: Rare	Impact: Medium	Risk: Medium

Measures: The hook was designed in a way that it can be easily replaceable by only loosening two screws. First, the one which holds the pulling spring in its place, and second, the one which secures the bolt of the hook.

Probability: Rare	Impact: Minor	Risk: Low

8 Conclusion

8.1 Final System Overall

The final mechanical system has a very simple design that fits very well with Lio. Mechanical loads within the expected range can be absorbed without any problems. The concept for the ArUco marker with the mounting for the laundry cart is also very successful and can be used as expected for various laundry carts.

The electrical interface operates within the expected range and the functionality of the spring contacts in conjunction with an Add-On is very satisfactory. The ESD standards have also been met, which is very important because electrical contacts are accessible to the end user when the rubber lid is removed.

The navigation of the robot to attach to the laundry trolley, as well as the interruption of the movement when the traction force becomes too great works perfectly, as will be seen in the chapter 8.2.

As can be seen in appendix 4, the total costs for the one-off production of the system amount to almost exactly CHF 100. Considering the one-time investment for the stencil plate and the fact that a filament roll is sufficient for three Add-Ons, the total price can be set at around CHF 67. Screws and general fasteners were not specifically included, as these are mass-produced items and can be found in stock.

8.2 Success Rate

Before engaging in the success rate topic, it is highly recommended to have read the chapter 6, to understand the processes described in it.

30 attempts of the normal docking process, the new alignment, the releasing of the cart and also the movement interruption if the pulling force was too great were carried out. Each attempt was successful, and not one failed. Hence, no further tests were conducted.

Another topic on which the success rate should not be neglected is the mounting of the Add-On onto the Add-On interface itself. Hence, if the spring contacts of the electric interface touch the spring counterpart the right way. To test this, the Add-On was simply put on the Add-On interface, then the hook was lifted with the linear switch, after which the push button was read out, and finally, the Add-On was removed again, repeatedly 30 times in a row. Like the other success rate tests, a 100% rate was also achieved here.

8.3 Problems and Critical Thoughts

In terms of the mechanical build, nearly everything is made from PLA with the help of a 3D printer, which does take some time until all parts are printed. The cable management through all cable channels can sometimes be a little bit tricky, especially the final assembly phase, where the lid closes the mechanism. The electromagnetic linear switch is weaker than described in the data sheet and is not able to lift up a hook which is made out of aluminium as computed in chapter 5.4. In addition, to rotate the lever back to its centre the two rubber parts are also not ideal to do that.

Even though the electric interface works as expected, the whole concept of controlling the hardware components by putting them in series with a transistor is not ideal. Imagine of sending a control signal for a servo motor. With the current system it is not possible to directly send a voltage signal to one input of an actuator without establishing a circuit on the spring counterpart.

The whole programming part was kept very simple and requires a lot of additional work to provide a final solution for a customer. In the current case, if Lio bumps into something during the docking process, he will just stop without any further procedure.

8.4 Answer Research Questions

8.4.1 Which components and design ideas can be used to develop a docking system?

The current passive docking system with the hook and the standardised counterpart on the cart offers a good general solution. However, gripper or claw systems may be developed for future carts.

8.4.2 Which possibilities exist to meet standards in terms of electronics?

In addition to the measures mentioned in chapter 3.3.1, components such as ferrite chokes can also be used to achieve certain standard categories.

8.4.3 What different kind of electronical hardware intersections would be appropriate between the Lio and the Add-On?

The current solution with the springs on the electrical interface and the counterpart on the Add-On offers a very handy solution compared to known intersections such as USB or other plug connections. By using the Add-On interface mechanism, the connection can be established with a single handle.

8.4.4 What mechanical design idea offers a good solution to integrate the Add-On and the interface into the Lio Robot?

The Add-On can be quickly mounted and dismounted via the Add-On interface mechanism without loosening any screws or other fasteners.

The mounting of the electric interface below the Add-On interface has the great advantage that there is enough space and mounting options. In addition, the cut-out in the cover can be concealed.

8.4.5 Which techniques can be used to steer the robot to the right position?

The most promising navigation technique for further progress of this bachelor thesis is to work with the existing mapping algorithm in addition to the implemented visual navigation.

8.5 Recommendations and next Steps

This chapter briefly describes the next recommended steps of the whole project in the topics electric interface, mechanical build and the programming. Some of the following tasks were discussed during the meetings and could have been implemented, but due to time management, these topics have been reserved for the next steps.

8.5.1 Electric Interface

The current solution to control electrical components with the electric interface by putting them in series with a transistor is not ideal. A far better solution would be by implementing something like a high-side-switch IC on the interface to directly offer a specific voltage at the output.

To fulfil the EMC standards, the electric interface could be equipped with a choke as described earlier.

8.5.2 Mechanical Build

To centre the lever better towards the middle, a solution would be to attach two pulling springs to the side of the lever instead of the rubber buffers.

Given that the electromagnetic linear switch is very weak, another actuator, such as a servo, could be used to lift the hook. This would also make it possible to integrate an aluminium hook.

If the cart docking Add-On is used by a customer, it is also worth considering adapting the whole docking concept slightly, as it is quite likely that there are better docking mechanisms depending on the laundry cart.

8.5.3 Programming

As mentioned several times, the programme still needs to be greatly expanded before it can be used by a customer. This topic will therefore not be discussed further.

One thing which can easily be implemented to handle the issue that the lever is not always centred in its middle, is by equipping the lever itself with an ArUco marker to always know its position and to take it into account when navigating to the laundry cart.

In order to find the laundry cart on an entire floor, the program can be extended with the already existing mapping algorithm in order to save the rough positions of the carts and then move to these stored positions again.

In order to familiarise nurses and customers with the system, a visual guide could be created via the myP interface.

8.6 Acknowledgements

I will take this opportunity to thank my supervisor, Gion-Pol Catregn, for his valuable support, patience, and helpful feedback throughout the project.

My thanks goes also to Abdelrahman Shalaby for providing the necessary resources and his constant willingness to help.

Not to forget is also Vincenco Di Toro, who helped me a lot with the EMC and ESD issues and also carried out all the tests with me. I really enjoyed working with him.

But my fellow students shouldn't be neglected either. I would like to thank, Deborah Schrag, Joel Flepp, Joshua Stutz, Lukas Marti and Florian Bütiker for their time and contributions. In addition, I would like to give special thanks to Tim Barmettler, who took the time to read my report all over again to point out any errors.

Last but not least, I would like to thank my family and friends for their support and understanding during the intensive work phases.

9 Register

9.1 List of Figures

9.2 List of Tables

9.3 List of Formulas

9.4 Bibliography

[1] "Über uns - F&P Robotics AG." Accessed: Apr. 02, 2024. [Online]. Available: https://www.fp-robotics.com/de/about-us/

[2] "Lio - F&P Robotics AG." Accessed: Apr. 02, 2024. [Online]. Available: https://www.fp-robotics.com/de/lio/

[3] "Overview of Lio: sensor and hardware setup. | Download Scientific Diagram." Accessed: Apr. 02, 2024. [Online]. Available: https://www.researchgate.net/figure/Overview-of-Lio-sensor-and-hardware-setup_fig1_342759990

[4] "Robotic Gripper Collection - YouTube." Accessed: Apr. 11, 2024. [Online]. Available: https://www.youtube.com/watch?v=EU6_hBsRQQQ

[5] "EMC Check - TARGET 3001! PCB Design Freeware is a Layout CAD Software|Support, Tutorials, Shop." Accessed: Apr. 12, 2024. [Online]. Available: https://server.ibfriedrich.com/wiki/ibfwikien/index.php?title=EMC_Check#Improvement_of_EMC_properties

[6] B. Dobkin and J. Hamburger, "Analog circuit design. Volume 3, The design note collection," p. 1104.

[7] "P-Rob 3 User Manual."

[8] "TPS6293x 3.8-V to 30-V, 2-A, 3-A Synchronous Buck Converters in a SOT583 Package," 2022, Accessed: Jul. 11, 2024. [Online]. Available: https://www.ti.com/lit/ds/symlink/tps62933o.pdf?ts=1720680430302&ref_url=https%253A%252F%252Fwww.mouser.ch%252F

[9] A. Einführung, "EMV & SAFETY," 2023. [Online]. Available: https://europa.eu/youreurope/business/product-requirements/labels-markings/ce-marking/index_de.htm#:~:text=Das%20CE%2DZeichen%20ist%20ein,in%20der%20EU%20vermarktet%20werden

[10] "A Guide to Understanding Common Mode Chokes | Coilcraft." Accessed: Jul. 26, 2024. [Online]. Available: https://www.coilcraft.com/en-us/edu/series/a-guide-to-understanding-common-mode-chokes/

[11] "3 Ways To Brick Your Raspberry Pi | Twilio." Accessed: Jul. 13, 2024. [Online]. Available: https://www.twilio.com/en-us/blog/3-ways-brick-raspberry-pi

[12] "Power Consumption Benchmarks | Raspberry Pi Dramble." Accessed: Jul. 13, 2024. [Online]. Available: https://www.pidramble.com/wiki/benchmarks/power-consumption

10 Appendix

1. Manuals
   Brief Description: Includes all important manuals for the bachelor's thesis.
   File: Manuals
   Date: 29.02.2024
2. Fact Sheet
   Brief Description: Task description of the bachelor's thesis.
   File: Fact Sheet.pdf
   Date: 20.02.2024
3. Timetables
   Brief Description: Consists out of the ideal timetable and the adapted timetable
   File: Timetables
   Date: 15.07.20254
4. Order List
   Brief Description: Includes all necessary components for the final product with links and prices
   File: Order_List_Bachelor_Thesis.xlsx
   Date: 15.07.2024
5. Electrical Interface and Spring Counterpart Altium Files
   Brief Description: Contains all Altium files of the created PCBs
   File: Electrical Interface and Spring Counterpart Altium Files
   Date: 05.06.2024
6. Schematics Lio
   Brief Description: Electrical schematics of Lio type b and c
   File: Schematics Lio
   Date: 04.03.2024
7. Data Sheet TPS62933O
   Brief Description: Data sheet of buck converter
   File: Data_Sheet_TPS62933O.pdf
   Date: 01.03.2024
8. Data Sheet 100nF Capacitor
   Brief Description: Data sheet of 100nF capacitor
   File: Data_Sheet_cl10f104zb8nnnc.pdf
   Date: 07.05.2024
9. EMV and ESD Standards
   Brief Description: Contains all files for the topics EMV and ESD standards
   File: EMV and ESD Standards
   Date: 01.07.2024
10. CAD-Files
    Brief Description: Contains STL and G-Code Files to manufacture all parts
    File: CAD
    Date: 02.08.2024
11. Software Files
    Brief Description: Contains all scripts for myP to control Lio
    File: Software Files
    Date: 02.08.2024

Declaration in Lieu of Oath

«I hereby declare that I have completed this work independently and have not used any other means than the specified sources and permitted resources, including the use of AI systems. I have indicated all passages which have been derived from out-side sources either literally or in their general substance. I followed the guidelines for scientific work. I am aware that, should I have failed to do so, the University Administration is entitled to revoke the qualification or title granted to me on the basis of my work. »

Name: **Place, Date:**	**Signature:**
Yan Gridling Flumserberg, 05.08.2024	