Internship Report

Implementation of MRI-compatible stepping robot MARCOS II

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Contents

1. Introduction

1.1 About the Lake Lucerne Institute

The Lake Lucerne Institute (LLUI) is a center for interdisciplinary research located in Vitznau and Hertenstein adjacent to the Cereneo Center of Neurology and Rehabilitation in Switzerland. As a team of young researchers, they are motivated to close the gap between industry, academia, and the clinic for improving rehabilitation. Therefore, projects are developed and carried out in constant interaction with patients, caregivers, and clinicians. Located in Vitznau and Hertenstein are the movement lab CAREN, a 3.0 Tesla MRI, various IMU sensor systems, and a variety of therapeutic devices of all disciplines[1].

The robot, whose implementation is subject of this internship is located next to the MRI in Hertenstein.

1.2 Purpose of the Internship

MARCOS II is an MRI-compatible stepper robot, that is based on MARCOS, which was developed at the Sensory-Motor Systems Lab at the ETH in Zurich, CH. It is a one-degree-of-freedom robot that can provide active and passive gait-like movements during fMRI, without negatively affecting the quality of the images [Marchal-Crespo et al., 2011]. MARCOS II was set up at the clinic in Vitznau and operated until the MRI was moved to Hertenstein. The robot was disassembled and moved to Hertenstein, but not set up again.


Figure 1.1: On the left: Original setup of MARCOS II in [Marchal-Crespo et al., 2017]; On the right: present setup of MARCOS II in the dressing room of the MRI in Hertenstein

The purpose of this internship is to reassemble the MRI-compatible stepping robot MARCOS II, bring it back to operational mode, and install it in the MRI. If time allows for it, a behavioral experiment (e.g. game) is to be programmed for experiments using the robot, to further investigate the neural correlates of lower limb movement.

1.3 Duration of the Internship

The internship starts on the 1st of September 2023 and has a duration of 3 months. It ends on the 30th of November 2023.

[1] https://www.llui.org/

2. Objectives of the Internship

2.1 Personal Objectives

For me, this internship is very exciting because it represents a career entry into the world of medical technology. I already chose subjects in the fields of medical technology and robot-assisted surgery during my undergraduate studies. With this internship, I want to understand what it is like to work in such a field. I am also working in a young and dynamic team with other scientists, which allows me to gain insight into other areas of medical technology. Furthermore, I find the experience of working in a rather small company in Switzerland very exciting. As this is an interdisciplinary field, the work is varied and very interesting because I can deepen my knowledge from various projects at my university and from my free time.

2.2 University Objectives

This internship is part of the MSc. Robotics can be chosen in the first quarter of the second academic year. It accounts for a total of 15 ECTS [1]. Requirements by the faculty 3mE at TU Delft include finding a supervisor for the project. Dr.ing. L. (Laura) Marchal Crespo agreed to be my supervisor for the project.

2.3 Organization Objectives

From the side of the Lake Lucerne Institute, Josua Zimmermann (MRI Lab Manager) is my supervisor for the project, and Chris Awai (Managing Director of LLUI) is my legal supervisor.

2.4 Overview of the capabilities of MARCOS II

As briefly mentioned in section 1.2, the main task of the internship is to re-assemble the robot MARCOS II in the MRI lab of the Hertenstein clinic. MARCOS II is a pneumatically actuated magnetic resonance compatible stepper robot developed for the investigation of brain activation of lower limb motor control with functional magnetic resonance imaging (fMRI) [Jaeger, 2013].

This robot is unique in its capabilities and movements and can move the participant's leg actively, as well as adapt to the human gait to follow their movement, by minimizing the forces between the robotic system and the subject. From the paper by Marchal–Crespo et al., 2014, four training modes can be identified:

- **Haptic-guidance mode:** The position controller adjusts the knee trajectory by controlling the proportional flow valves based on the difference between the desired and measured knee positions. The Iterative Learning Controller (ILC) leverages the cyclic nature of gait movements to enhance overall control performance by generating a feedforward control signal for each step from the error trajectory of previous steps.
- **No-guidance mode:** In no-guidance mode, the robot moves synchronously with the user's voluntary motions and aims to minimize interaction forces, allowing the user to move freely

[1] https://www.tudelft.nl/onderwijs/opleidingen/masters/robotics/msc-robotics/programme

without sensing the robot's presence. The control strategy employs a closed-loop force controller to counteract the orthosis' weight at the knee joints.

- **Error-Amplification mode:** In error amplification mode, MARCOS magnifies tracking errors during knee movements by adjusting the force output based on the difference between the desired and measured positions. The negative proportional gain (Kamp = -2 N/m) ensures smaller forces for smaller errors and increases the force with larger tracking errors. Safety is maintained by limiting the magnitude of the amplified force.

- **Noise-disturbance mode:** On top of the closed-loop force controller described above, in this mode a random force is induced by the knee cylinder for 0.1s every 0.5s. It is generated by a random white noise block in Simulink and limited to an amplitude of 100N.

2.5 Description of how the robot system functions:

The MARCOS II robot is a very complex system, consisting of multiple parts with different functions. The main components are as follows: There is one pneumatically actuated unit to move the feet, and one to move the knees of the subject. The knee unit moves up and down when compressed air is flowing in and out of the pistons. It can also rotate around an axle in the knee unit. The foot unit also consists of two pistons which are pneumatically activated. The foot position can manually be adjusted. These two units are screwed onto the bench of the MRI with plastic sliding parts and screws, along with fixations for the hip and the shoulder of the subject to prevent excessive head motion. The subject is further supported by a vacuum pillow for the back, and a vacuum pillow for the head of the subject. The feet are connected via straps with the robot, the knees via modified knee orthoses, that connect to the knee pistons via carbon hangers.
The force and position of the knees and feet are measured, amplified, and converted to an optical signal by the E-box inside of the MRI room. The circuit for the emergency stop of the subject is also inside the E-box, and the emergency stop for the subject is at the bench of the MRI. An optical cable for the signal transmission, as well as a power cable, connects the E-Box and the Control Cabinet, which is located inside the technical room of the MRI and shielded from the magnetic field. The Control Cabinet holds all the pneumatic valves to control the airflow going to the MARCOS. It is directly connected to the robotic system via pneumatic tubes. The Control Cabinet is also connected to a second emergency stop for the operator, and to the xPC Target computer via an EtherCAT cable. The xPC Target runs the compiled Simulink model, which is compiled on the Control Computer running MATLAB ™ 2013b in Windows 10. The two computers are interconnected via an Ethernet Cable for the xPC Target Real-Time engine of MATLAB, and via USB to Serial for the software Presentation™. The MRI can be activated using a D-SUB9 adapter with a serial connection.
A sketch of the robotic system with all the connections can be seen in figure 2.1.

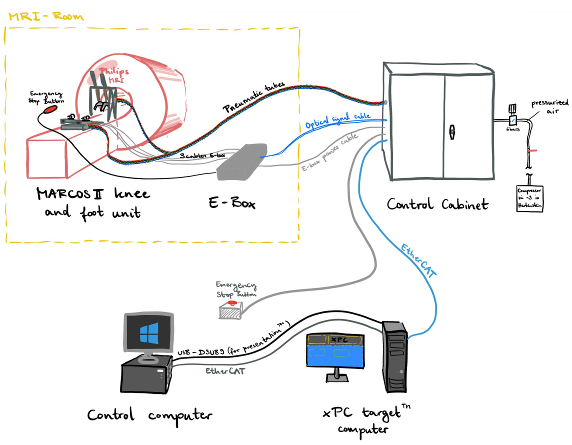

Figure 2.1: Overview of the interconnected components of MARCOS II

3. Description of Internship Activities

3.1 Inventory of the robotic system

At the beginning of my internship, I did an inventory of the robotic system MARCOS II. Fortunately, the knee and foot units were still assembled. I inspected all mechanical parts of the robot and gently tightened all screws in reach. All moving parts were tested for functioning properly, and all sensors were inspected by sight. Furthermore, I connected all loose cables and components that were lying around. The provided MARCOS II manual was very valuable in this process. At the robot, some parts did not belong to the MARCOS II robot and were put away.
The following items were missing:

- *The knee orthoses:* The two Ottobock Genu Arexa knee orthoses [1] were missing. As described in the manual, these orthoses were modified to make them MRI-compatible Jaeger, 2013.
- *Vacuum pillows:* The vacuum pillows for the back, as well as for the head were missing.
- *The pressurized air connection:* The MARCOS II control cabinet was not connected to a pressurized air supply. However, a connection to the MRI technical room from the compressor at Hertenstein Clinic had already been made.

The *Ottobock orthoses* were ordered again from https://www.ottobock.com. Thankfully, Dr. Peter Wolff provided me with the size information (Large) and the CAD files for the modification. The screw, joint, and pin had to be manufactured from aluminum, as well as a hanger from carbon, to fix the knee orthoses in the mounts of the knee unit.
The *vacuum pillows* for the original MARCOS setup were ordered at https://www.synmedic.ch/. Since this company has stopped with distribution of parts, we instead decided to order the parts at https://www.pearl-technology.ch/, once the MARCOS is in a working state. They offered to come by and propose a solution, but since the robot was not in the working state of my internship, we have not ordered the parts yet.

Calculation of air supply for MARCOS II

The *air supply* that is needed for powering the MARCOS II robot can be calculated using the following equation:

$$\dot{V} = \frac{2fsFn}{p_a} \tag{3.1}$$

The maximum stroke of the cylinders is $s = 0.32m$, the maximum frequency $f = 1.5Hz$, and the estimated Force up to $F = 350$ at $\eta = 0.85$ and $p_{cylinder} = 6bars$. With an ambient pressure of $p_a = 1bar = 10^5Pa$ and the number of cylinders $n = 4$, equation 3.1 equates to $\dot{V} = 0.00672\frac{m^3}{s} \approx 806\frac{l}{min}$. The compressor required to operate the MARCOS II robot must therefore be very powerful. Unfortunately, the compressor that was used to operate MARCOS II in Vitznau cannot be moved to Hertenstein, as it is still used for the Allegro Robot there. The compressor located in Hertenstein with a maximum air flow of 150l/min however is sufficient for testing MARCOS II, but not for the operation of the robot under maximum load. We, therefore, decided to order a rotary screw compressor at

[1] https://www.ottobock.com/de-ch/product/50K13

https://www.toesstal-vertrieb.ch. Its specifications are as follows: 11kW power, air supply 1400l/min at 10 bars maximum pressure, tank size 500l. The compressor is currently located in the basement of the Hertenstein clinic and needs to be connected to the Control Cabinet of MARCOS II.

3.2 Modification of parts of the system

Due to the larger distance between the control cabinets, some parts had to be modified accordingly:

- **Connection control cabinet - xPC Target:** Since the distance between the control cabinet and the xPC Target is greater than before, we decided not to extend the EtherCat cable, but to get a longer one. It was installed by an external company and laid in the ceiling from the technical room to the MRI computer room.
- **Emergency Stop operator:** The emergency stop is located right next to the control computer and connected to the control cabinet. In the original setup, a seven-core cable was used. The connection however only has five pins, so two cores were not being used. Therefore, I decided to use a five-wire cable, desoldered the old wires that were attached to the connector, and soldered the new cable back to the connector (see figure 3.1. After the cable had been laid into the ceiling by an external company, I tested the Emergency Stop button for functioning.

Figure 3.1: Old cable on the left, new cable on the right

- **Connection control cabinet - MARCOS II:** The MARCOS II robot is supplied with pressurized air from the control cabinet. Since this distance in Hertenstein is greater than in the original setup in Vitznau, these pneumatic hoses had to be extended. This is unfortunate, as longer air hoses will most likely negatively affect the control of the robot. I decided on 8mm push-to-connect fittings from Festo, as these are easy to re-attach if the hose length changes, and they were being used inside the control cabinet as well. The hoses were extended with a standard 8mm pneumatic hose by Festo and color-coded using isolation tape. The extension was about 4 m for the hoses leading to the foot unit, and 5 m for the ones connected to the knee unit. The hoses were then covered with a polyester sleeve for protection and sealed with heat-shrink tubing.
- **Optical cable:** The length of the optical cable was sufficient to connect the Control Cabinet to the E-Box. As this cable is very fragile, I covered it in a polyester sleeve and laid it on the ceiling of the technical room of the MRI.

3.2.1 Knee Orthoses

About 8 weeks into the internship, the knee orthoses Genu Arexa from Ottobock (size: Large) arrived. From the CAD Files that Dr. Peter Wolff had provided, I could see how the knee orthoses were modified to make them MRI-compatible, and how to attach the carbon hanger.

Carbon Hanger

Among the provided CAD files of MARCOS I was the design of the carbon hanger for attaching the knee orthoses to the knee pistons of the robot. Following a tutorial from EasyComposites [2], I designed

[2]Video Link: https://www.youtube.com/watch?v=4ND2WtEZatY

a mold for making the carbon hanger in Fusion360 and used a 3D printer to make the part (see figure 3.2).

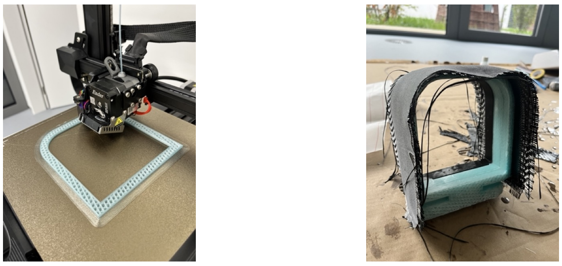

Figure 3.2: Printing and laminating the carbon hanger

In the following steps, the 3D-printed mold was coated with an anti-stick solution, then epoxy resin was mixed with hardener, and several layers were hand-laminated onto the mold. The number of layers depended on the weight of the carbon fiber cloth. For the first prototype, I did not use enough layers for the thickness of the cloth, therefore it turned out to be a bit too thin. Once the part ad hardened, I cut off the excess carbon fibre cloth with a diamond cutting wheel and a Dremel, and applied a finishing resin mixed with hardener.

Figure 3.3: Suspension of carbon hanger MARCOS II

Once this coating had dried, I sanded down the piece and drilled the holes for attaching the hanger to the knee orthosis. Contrary to the carbon hanger that was designed for MARCOS I, the suspension for the carbon hanger of MARCOS II does not require four drilled holes on the top side of the hanger (see figure 3.2). As it can be seen in figure 3.3, the first prototype of the carbon hanger turned out to be successful. However, as not enough carbon fibre cloth was available yet, it is not quite thick enough. I made two more carbon hangers with 5 laminated layers of carbon fibre cloth with a weight of $400g/mm^2$ to reach a total thickness of 4mm for the hanger. As the material was too thick for the Dremel to cut through, my successor will have to finish the carbon hangers with an angle grinder, which will be available then.

CNC-Machine

To make the knee orthoses MRI-compatible and to attach the carbon hanger, the parts need to be modified. We could identify two small stainless steel screws on the bottom and the top of the knee orthosis, that were slightly magnetic. Furthermore, an aluminum part needs to be crafted to attach the carbon hanger to the orthosis. These parts can be manufactured using CAM software, a CNC machine with a 2mm drill, and a thread milling cutter. Since the Stepcraft M.1000 CNC machine arrived completely disassembled, one of my side tasks consisted of building and implementing the CNC machine. After all the parts were assembled, the wires had to be cut to length and attached to the CNC circuit board. I used the newly assembled computer, which was originally meant to serve as the xPC target computer (see section 3.3.2), as a designated computer for the CNC machine. The computer runs the UCCNC Software in Windows 10, which can be used to directly control the CNC machine and to load the G-Code files on the machine. At the end of my internship, we were able to get the Stepcraft M.1000 running, and we milled the Stepcraft Logo into wood using a sample file (see figure 3.4).

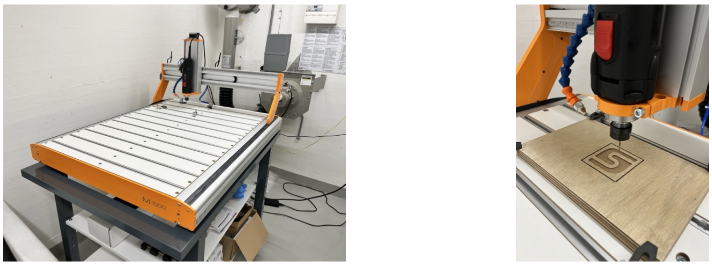

Figure 3.4: Assembled CNC-machine

For the modification of the knee orthosis, my successor will have to build the parts inside of the CAM Plugin in Inventor Professional, which I installed on the computer in the fishtanks of Villa Magdalena in Vitznau (see for the design of the part in the CAD folder in MS Teams).

3.3 Fixing of broken components

3.3.1 Repair of the xPC Target computer

Unfortunately, the xPC target computer running the compiled Simulink control model would not turn on. With the help of Steve Hughes from IT, we inspected the computer and concluded that the power supply unit was broken. Since it was not modular and some connections were outdated, I ordered the exact same unit (LC5550 V2.2) and we put it into the computer. The computer now turned on, the CPU started and all fans were running, but a connected monitor was not receiving any signals, although I tried all three display ports and two different monitors. Also, the control computer did not recognize any connected xPC computer in Matlab. As the computer was not even logging, we concluded that something on the motherboard was defective.

3.3.2 Build of a new xPC Target computer

As the motherboard is a model from 2006, and trying to fix it might lead to even more broken components, we decided to build a new computer to configure it as an xPC Target. Since two Ethernet ports were necessary, we decided for the MSI Z790 Gaming pro Wifi and an Intel i5 chip 12th generation. After my colleague André and I had assembled the new computer, I tested it with Ubuntu 22.04. Even though everything seemed to work, we could not configure the computer as an xPC target. This is likely due to compatibility issues of the new chip architecture and the motherboard, as the xPC interface repeatedly reported that no VBIOS support was detected on this card. I tried changing all relevant xpcenv configurations for the xPC Target, which I logged in an Excel sheet. The computer was later used for the CNC machine (see section 3.2.1).

3.3.3 Fixing of the old xPC Target Motherboard

As the newly configured xPC target did not work and the old one was disassembled, I inspected the old motherboard again and found a blown capacitor underneath the GPU. We ordered the same capacity, and I soldered it onto the old motherboard. To my surprise, this capacitor seemed to have been the only broken part, as the computer booted from the USB Stick into the xPC target interface.

3.3.4 Connection of Host and Target Computer

To run the compiled SIMULINK model for the control of MARCOS II on the xPC target computer, it must be connected to the host computer via an Ethernet cable.
A common way to test this connection is using `ping` from the command line tools in Windows.
However, the ping transmit failed. We debugged the most likely causes for the ping transmit failure, among them were the following:

- Network Interface Card (NIC): Replaced the NIC with the exact same model

- NIC Slot: Tried all slots in the motherboard for the NIC
- Tried using an Ethernet Switch between the host and target computer
- Used a crossover cable (as this can resolve connection issues for older computers)
- Temporarily disabled the firewall on the host computer
- Configured a static IPv4 address on the host computer, and disabled the IPv6 address
- Reset the DNS cache and winsock on the host computer

All of the above tries resulted in the same "ping transmit failed"-error. We tried pinging another computer from the host computer, which worked.

Further Steps with the xPC Target Computer

After numerous attempts trying to connect the host computer with the xPC target, we decided to finally borrow an xPC from the University of Basel, which used to be part of a rowing simulator. Unfortunately, using this computer resulted in the same error - ping transmission failed. Since it can now be concluded that the problem lies within the configuration of the host computer, further investigations should focus on that computer.
What could be tried, is for example downgrading the Windows 10 Professional to an earlier version, or trying to ping the xPC using another older computer (preferably older than 2015) with a disabled firewall. Also, different configurations for the IP address settings could be tried on the new PC.

3.4 Other projects

3.4.1 MRI-compatible gaming-controller

As part of my internship, I modified a gaming controller following to the paper of Trees Trees et al., 2014 to make it MRI-compatible. This controller can then be used for future research on brain activity during gaming, and even for Metastudies using multiple MRIs. At first, we bought an original Playstation 2 controller, but due to the difficulties interfacing the controller with an Arduino Uno to test its functionalities, we decided to go with a 3rd party gaming controller with a USB interface. The main tasks of the modification of the gaming controller to make it MRI-compatible were the following:

1. Disassembling the gaming controller
2. Desoldering all parts of the gaming controller that are magnetic (i. e. the vibration motors, buttons under the joysticks, joystick casings, see figure 3.5)
3. Creating custom replacements for the necessary magnetic parts of the gaming controller
4. Replacing the main cable with a shielded cable, soldering it to the circuit board, and adding a cable that grounds the gaming controller casing by connecting it to the ground of the MRI room
5. Applying a copper-silver spray coat to the inside of the controller casing (see figure 3.5)
6. Reassembling and testing the gaming controller

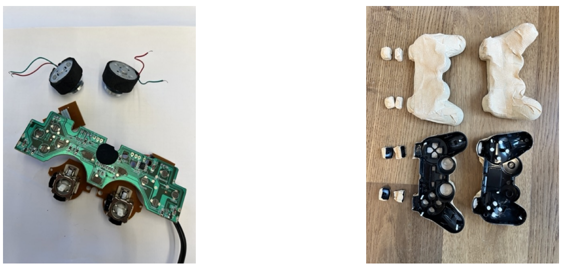

Figure 3.5: Desoldering of the magnetic parts and preparation before the spraycoating

4. Skills Acquired

Due to the great variety of tasks that I was assigned, I acquired and improved a wide set of new skills during this internship. This includes:

- **Computer assembly and architecture:** During the process of trying to get the xPC running, I learned how to disassemble and assemble computers and acquired a basic understanding of computer architecture.
- **Soldering:** During the repair process of the xPC target computer and the modification of the gaming controller, I was able to improve my soldering skills, especially with small parts on circuit boards.
- **3D-printing:** For modifying the gaming controller, the joystick casings had to be replaced by 3D-printed ones. Also, for the custom carbon hangers, I needed to design and print the 3D-printed molds. During this process, I learned debugging and operating a 3D printer and improved my CAD skills.
- **Making carbon parts:** I had never worked with Carbon before, so making custom carbon parts was a new challenge for me. During the process, I learned a lot about the material, its components, and how to produce custom parts.
- **MATLAB Real-Time:** Even though I was already familiar with MATLAB and SIMULINK before my internship, I learned a lot about MATLAB Real-Time and the configuration of an xPC Target.
- **CNC-Machine:** As I had the chance to build the CNC machine from an assembly kit that was ordered, I learned how a CNC machine works and how to operate it.
- **Pneumatics:** Since the MARCOS II robot is operated using pressurized air, I learned how a pneumatically actuated robotic system works, and how to calculate the necessary air for that robot.

5. Personal Reflection and Lessons Learned

For me, one of the most valuable things I learned during my internship was what it is like to work in a small but fast-growing company in Switzerland. The work environment was very different from what I had experienced during my internships and work at large, international companies such as Audi AG and ZF Friedrichshafen AG. I had the chance to get to know the medicinal technology area, which I could imagine myself working in after my studies. I liked that the work I did seemed meaningful to me, as the technology might help to improve people's lives in the future. I also really enjoyed having the responsibility for my project and I felt honored, to be able to work on such a complex and advanced robot by myself. Making great progress in its implementation made me confident to succeed in future projects.
It was also new to me how quickly decisions can be made to drive a project forward if sufficient resources are available and if there is a flat hierarchy. This was different from the prior work experiences I had had.
I enjoyed working and living in Switzerland. The young and dynamic working environment, great colleagues, superiors, and supervisors, and beautiful surroundings made my internship really enjoyable. Furthermore, the projects and tasks I was assigned reflected my interests, as I find it fascinating to work on robotic systems, and the medical technology field is very interesting to me. I am now more confident, that I will be able to bring great value to a company after I have finished my MSc. Robotics program.

During my internship, I learned some lessons and discovered things that I would try to look out for in future projects.
First of all, for me, the value of good documentation became clear during this internship. The provided manual was crucial for the understanding and the implementation of the robot, without it this would have not been possible. However, in many details, the manual was missing in-depth information, which had to be gathered manually (for example the size of the Ottobock orthosis, or the general setup on which cables were connected, etc.). For the SIMULINK model, however, the structure of the code files and the model itself are unclear. This makes it very complicated to understand the program and how to change the model for future experiments. For future projects, I would try to look out for working with reliable and good equipment. Soldering, for example, was quite a challenge as the cheap soldering iron available did not get hot enough to dissolve the solder on the computer's motherboard, and on the gaming controller, the heat applied was not spot on enough, damaging the board. To be fair, the gaming controller failing in the end might have been due to my soldering skills as well, however proper clamps and a decent soldering iron would have made the process easier. Fortunately, LLUI will be blessed with a great workshop in the future, that is set up shortly after my internship (along with a fume extractor). However, at the time of my internship, this was not yet the case.
I also discovered the value of having a workplace close by. Having a distance of about 100m between my flat and my work might have been even too little, but a commute time of 2 minutes per day gave me enough time to work on personal projects, do a lot of sports, and relax during my internship, which I found to be very valuable. Furthermore, it became clear to me how important I find it to have a good relationship with co-workers and my superiors. Since working together with my colleagues and superiors was easy, I thoroughly enjoyed working and had enough energy at the end of the day to keep pushing the project. O a few days, there was an argument with a co-worker about the defective 3D printer, which considerably drained my energy.

6. Conclusion and final words

Overall, my internship in Switzerland was a great experience. I thoroughly enjoyed the project, the work environment, and the surroundings at Lake Lucerne Institute in Switzerland. It gave me the chance to work on a unique and very interesting robot, gave me insight into the work culture in a small company in Switzerland, and I had the chance to develop new skills that align with my personal interests. Also, it was a door-opener in the world of medicinal technology, which I find very compelling as a future field to work in.
I am very happy to note that the project is ongoing and that a very capable successor has been found to bring this project forward.

I would like to thank my supervisors Josua, Chris and Laura, who supported me in every regard with this project, whether it was for gathering new material or resources or working along trying to fix the xPC in long late afternoon hours or for any information or contact that we needed for the project. Also, I would like to thank my superior Lisa, who always helped me out when I needed new tools or materials for the project, and everyone else working at LLUI who was always there to help carry things or discuss how to solve smaller problems that occurred.

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