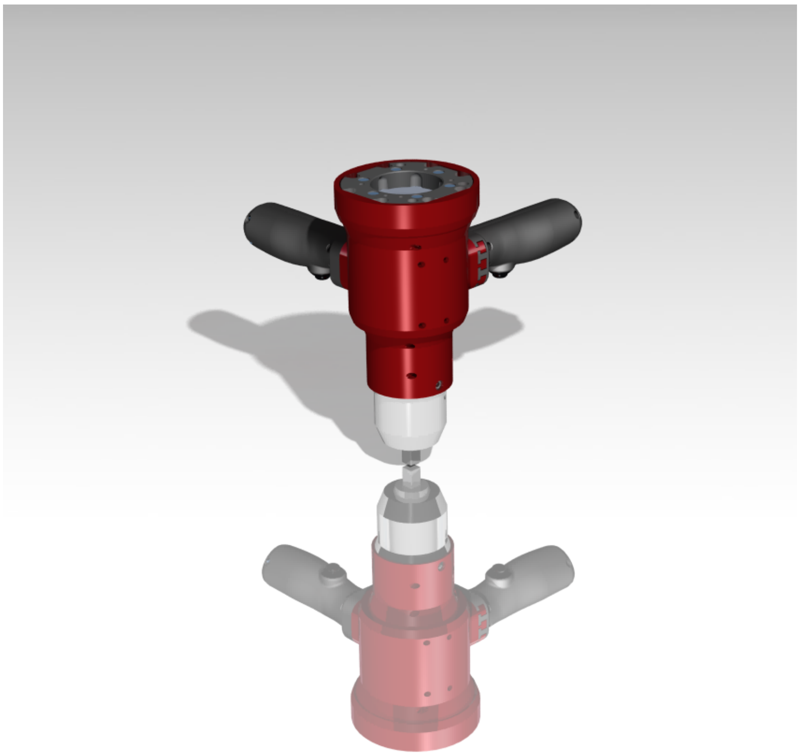

Design of a collaborative tool

Design of a generic tool for mounting/demounting of rotational design elements for use by robots and humans

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Bachelor's thesis 2017

Design of a collaborative tool

Development of a tool for use in collaborative assembly/disassembly with robots and humans in both industry and aftermarket services

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Cover: CAD assembly of tool body parts.

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Abstract

In today's industrial and manufacturing markets, companies are turning to collaborative robots in order to decrease labor costs and increase efficiency. As such, Volvo was seeking the creation of a tool which could be operated by both humans and collaborative robots in order to perform mounting and demounting operations of rotational design elements such as screws and bolts in their truck manufacturing processes.

This report details the project from concept selection and design to the finalized working prototype. The main customer needs included that the tool: be able to perform various mounting and demounting operations, be ergonomically designed for use by humans and robots, be able to produce a continuous torque of 70 Nm and a speed of 400 rpm, utilize the Robot Operating System (ROS) software platform and an RSP connector, be able to determine if a bolt had been entered correctly, and that it used a cordless power supply. The team used these customer needs to create four hand-drawn design concepts for the tool, and then weighed the requirements for each design. The final design was chosen, drafted into CAD models, and then 3D printed in PLA plastic. The tool consisted of three 3D-printed parts: the tool body, a detachable tool head, and two handles, which were located at a 90 degree angle from each other on the tool body. Furthermore, the team ordered an impact wrench in order to be able to reach the required high torques, and this was then reverse engineered in order to create the necessary connections with the purchased embedded system and speed controller. The embedded system consisted of ROS and a Raspberry Pi microprocessor, and these components enabled the tool to communicate with the overhead system in the manufacturing sites, via WiFi. Finally, an RSP connector was attached to the back end of the tool body in order to ensure that the tool could be attached to the respective RSP connector on the robot arms in the factory.

This project was global, meaning half of the team was in the U.S. and half of the team was in Sweden, and thus the budgeting and timeline information varies slightly. However, the report outlines that the team was able to remain within their Universities' allotted budgets of $1,000 and SEK 9000, respectively, and the team was also able to meet the required deadlines depicted in a Gantt chart, in order to successfully build the first prototype by the end of April, 2017. The report details recommendations for enhancements on future prototypes, and it concludes that the tool met the major customer needs. It ran at a speed of 800 rpm and it could reach torques of 160 Nm according to part specifications. The tool utilized an RSP connector and ROS to ensure that all robot capabilities could be employed and to allow the tool to know how many torque impulses to administer before stopping, and whether a tool was entered correctly or not. Finally, the report concludes with the team's rated self evaluation of whether or not the tool met the customer's needs and the global and societal needs.

Keywords: collaborative, assembly, tool, aftermarket, rotational, robot.

Sammanfattning

Inom dagens industri och tillverkning går fler och fler företag mot att använda kollaborativa robotar för att minska kostnader och öka effektiviteten. Ett företag som är på väg i den riktingen är Volvo Lastvagnar och för att effektivisera deras produktionslinjer letar de efter ett verktygssystem som ska kunna användas av både människor och robotar där verktygets funktion är att skruva i och skruva ur gängade fästelement både inom produktion och på eftermarkand. Målet med detta projekt var att konstruera en fungerande prototyp som ska möta de krav som har ställts på densamma.

Rapporten beskriver hur projektet gått från planering, framtagning och val av koncept, val av komponenter och konstruktion som lett fram till prototypen. Kunden, Volvo Lastvagnar, hade många krav och önskemål på prototypen, varav det stora flertalet kunde mötas. De viktigaste kraven gällde kommunikation med överliggande system via ROS, leverans av både hög rotationshastighet och högt och noggrannt moment samt funktionalitet för att detektera eventuella felaktigheter när fästelementet skruvas i med mera. Huvudkomponenterna till konstruktionen togs från en Milwaukee mutterknackare, och till det köptes ett drivsteg från Maxon Motors och en Raspberry Pi för att köra Robot Operating System, ROS, och därigenom sköta kommunikationen med överliggande system. Slutligen består det mekaniska gränssnittet till roboten av en verktygsväxlare från RSP.

Projektet har varit globalt i det att halva projektgruppen befunnit sig i Göteborg, Sverige och halva i State College, USA. Varje lag byggde var sin identisk prototyp, detta för att integrationen mellan komponenter inte skulle bli lidande av att de befann sig i olika länder.

Nyckelord: kollaborativt, montering, verktyg, eftermarknad, fästelement, robot.

Acknowledgements

The team would like to thank Petter Falkman and Jason Moore, both supervisors of this project for valuable input and feedback. The team would also like to thank Per-Lage Götvall, the team's sponsor at Volvo Group Trucks Techonology.

Also, a special thanks to Volvo Group and Monica Ringvik, Director of Research and Innovation Policy at the Volvo Group, Gothenburg, Sweden, for the financial support which made it possible for both the Chalmers students to visit Penn State University as well as enabling Penn State students to visit Chalmers University of Technology.

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Contents

List of Figures

List of Tables

1
Introduction

Volvo Trucks is one of the top contenders of heavy-duty trucks in the global market. In fact, they have such a large global presence that they are supported by over 2,300 dealerships and workshops, and they have a total of eight Volvo Truck-owned assembly plants, as well as nine independently owned factories. Though they provide trucks and various products and services all over the world, about 95% of the company is run in Sweden, Belgium, Brazil and the USA[1].

Volvo prides itself on being one of the world's leading innovators in quality, safety and sustainability, and as such, they are constantly trying to improve the way their trucks and other products are being created. Thus, with a strong focus on innovative methods, Volvo is working to improve the efficiency of their production lines by turning to collaborative robots. In today's market, there are currently collaborative robots which can perform certain manufacturing tasks, such as applying labels via adhesives, and screwing and unscrewing bolts. However, most robots that currently exist require the aid of humans to do the tasks, whereas Volvo is hoping to create a tool that can be used independently by a robot, without the need for any human assistance. The goal is to create a tool which can aid in Volvo's manufacturing process by both robots and humans alike, in hopes that this will increase efficiency and cut costs of production.

1.1 Initial Problem Statement

In today's industrial sectors, robots are rapidly changing the way things are mass produced. Volvo Trucks is hoping to use robots in order to improve the efficiency of certain production tasks carried out in the making of trucks, such as the mounting and demounting of rotational design elements. Currently, only humans are doing these rather simple and repetitive tasks, and Volvo hopes to design a system in which a tool similar to a torque wrench can be used by both humans and robots alike, in order to screw and unscrew bolts in a way that is quicker and more effective overall. Thus, this system must contain a tool-head which can be ergonomically used by collaborative robots and humans, a motor and drive system for the robot to obtain directions from, as well as a sensing system that allows the robot to sense where the bolts are spatially, and whether or not the bolt is being screwed in or out, and correctly at that. The end result should successfully improve efficiency of mounting and demounting operations used in Volvo Truck's manufacturing sites as well as servicing workshops.

1.2 Objectives

The goal of this project is to produce a working prototype that can be used by humans and collaborative robots to screw and unscrew bolts. Specifically, it should be battery powered and the robot should be able to screw a set of 8 bolts at a rate of 50 sets per every eight hours. More specifically, each individual bolt in the set should only take five seconds to screw in or out, and then it should take the robot ten seconds in between bolts to pick up a new bolt off of a work table and then begin to screw in the second bolt. Thus, to accomplish this, we expect the design to have a main part, containing all electronics and the drive system, that will be connected to the robot interface via a standardized size of an RSP toolchanger adapter. The tool head that will be performing the screwing and unscrewing of bolts will be a lightweight torque wrench that must be ergonomically designed so that it can be connected to the interface and used by the robot, and also so that it can be detached and used by humans.

One of the most important design considerations will be determining the best sensing/actuator system that can be installed since this will determine the accuracy and functioning capabilities of the robot. Of course, the goal is to produce the most efficient system at the lowest cost, but since this kind of tool does not currently exist on the market, the sponsor would like functionality and design to be the primary focus, and from there the costs will be evaluated accordingly. Thus, the biggest limitation for this project is discovering the optimal design of such a tool for use by a robot, and combining it with the optimal design of this tool for human use, all the while making sure the two are as easily interchangeable as possible.

2
Team and project management

2.1 Preliminary Economic Analyses - Budget and Vendor Purchase Information

At this stage, the budget analysis is a rough estimate of anticipated costs of the essential parts of the prototype, including the cost of the motor, the embedded system, the battery, drive system, sensors, and RSP TC connector. These costs can be found in Appendix C. In total, the team had a total budget of 2000 U.S. dollars. Apart from this, the budget also contains the cost of the planned trip for the Chalmers students to visit Penn State in April. The cost of the individual components can be found in Appendix C, not including building materials, which are provided by the workshops at Chalmers and Penn State respectively. The components for the prototype were purchased through the instructor at each university.

2.2 Project Management

Tasks and responsibilities within the project can be found in the Gantt chart in Appendix F. The project was split into three main parts: mechanical design, drive system and embedded system/software. Each subgroup had responsibility for management of each area.

2.3 Risks Plan and Safety

Due to the nature of the project, many risks are unique and thus creative solutions have to be made to minimize those risks. A table of the anticipated risks has been generated in Appendix G Table of risks. Unique problems such as communication difficulties are listed in the table and proposed solutions are listed as well. The level of risks was discussed in the group and color coded for easy access.

2.4 Ethics statement

All group members of Volvo Project 2 were committed to make impartial decisions, have a high moral standard, and act for a sustainable development throughout the project. Additionally, the group members were to act by the code of ethics set by American Society of Mechanical Engineers (ASME) in order to operate as fully-fledged engineers. As stated by ASME in the code of ethics, the group members were to respect intellectual property and proprietary information[2]. All group members were to work with honest intentions throughout the project and avoid any conflict of interest.

Furthermore, the team members would work in a professional manner in order to strive to increase the competence and prestige of the engineering profession. Moreover, Volvo 2 members were to strive for the enhancement of human welfare using their knowledge as engineers.

2.5 Environmental statement

Due to the fact that today's modern world faces big climate challenges, this makes the environmental aspect in this project very relevant. The group members would use their engineering skills in order to minimize the overall environmental footprint of the created product. In line with Volvo Trucks' core value of being pioneers within environmental care, the team members were committed to ensure sustainable development throughout the project[3]. Besides making all decisions throughout the project with the environment in mind, extra focus lay on carefully selecting materials and ways of manufacturing.

Furthermore, waste was to be handled with care and minimized whenever possible. It was the group's aim to deliver a product which both could meet the desired material properties as well as reduce the environmental impact at the same time.

2.6 Communication and Coordination with Sponsor

Primarily the communication between the team and the sponsor was conducted via emails, through a contact person from both PSU and Chalmers, namely Jen Nowoswiat and Staffan Björkdahl. The secondary mean of communication was through conference calls which were to be held on a regular basis with three weeks apart, with the reservation for any struggles with the schedule for both the team and the sponsor. Furthermore, the sponsor was emailed the team's weekly progress memos each Friday. Below is a list of previous and future scheduled communications:

- January 26, 2017 - First conference call with Per-Lage Götvall, Chalmers students met with Per-Lage at Volvo in Gothenburg.
- February 14, 2017 - Conference call with Per-Lage Götvall
- February 21, 2017 - Project proposal presentation
- March 30, 2017 - Mid Term presentation
- April 25, 2017 - Final Project Presentation (Penn State)
- May 23, 2017 - Final Project Presentation (Chalmers)

3
Customer needs assessment

3.1 Gathering customer input

Since the project entails developing a tool prototype for future tool development, the customer is the sponsor at Volvo Group, Per-Lage Götvall. The customer needs were given as a list of requirements, as well as gathered in a meeting with the Per-Lage and compiled into engineering specifications found in Appendix A. Also, some requirements regarding adherence to regulation, for example the Swedish work environment authority, were added. After searching the market for tools used in assembly today, it was found that cordless torque wrenches had an output of at most 70N m, whereas our customer wanted 150N m. Therefore, 70N m was put as a requirement, and 150N m was put as a request.

3.2 Weighing of customer needs

The customer needs were split in two categories: requirements that the tool must fulfill and requests that are beneficial and still important, but are not absolutely necessary, and thus will be completed if there is time. The requests need to be prioritized for the decision making in the future designing process. The priority of the requests were generated through AHP process by the whole team. The requests and their priority are shown in Table 3.1. The AHP table can be found in Appendix H.

Table 3.1: Priority of engineering specification requests

No.	**Request**	**Priority**
1	able to deliver a torque of 100Nm CW and 150Nm CCW	high
2	weigh as little as possible	normal
3	be as ergonomic as possible	normal
4	be as quiet as possible	normal
5	communicate if a screw has been entered correctly to an operator	high
6	modular design, one main part, ability to connect different tool heads	high
7	tool heads should be easily interchangeable	normal
8	be able to perceive its surroundings	low
9	be able to do processing of sensor data onboard	normal
10	service life of at least 3000 hours	low
11	easy to service, regarding battery replacement and lubrication	normal

4

External search

4.1 Mechanical interfaces

By request from the sponsor, the tool will use 1/2 inch socket connector and the robot will connect to the tool with an RSP toolchanger. Therefore, research on the interfaces was conducted briefly.

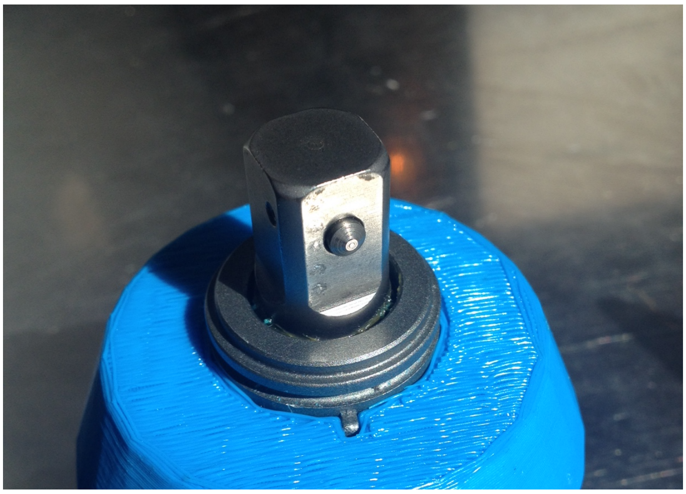


Figure 4.1: A 1/2" male socket connector

The socket connection interface consists of a square-shaped male/female fitting which snaps together. The related standard is called ANSI B107 which is widely used on torque wrenches. The standard makes it possible to snap on a wide variety of sockets which makes the tool able to mount numerous types of rotational design elements.

RSP is a Swedish company delivering, among other things, toolchangers for robots[4]. Using a toolchanger from RSP for the mechanical interface between the tool and robot is a customer requirement. Either the toolchanger TC-20 or TC-60 are to be used in the prototype, being able to cope with a torque of 100 and 600N m respectively[5][6].

4.2 Existing Products

This section details a search of products already on in the marketplace that was conducted in the beginning of the project. This was done to determine the best features currently working in industrial settings, as well as features that should be avoided.

Currently, there is a company called Fancort, which handles various automatic screw fastening systems through the use of Selective Compliant Assembly Robot Arm (SCARA) Robots. This company allows the customer to choose either electric drivers or servomotor drivers to control the mechanical operations the robot will be performing, such as fastening and loosening of the screw. The main difference in these drivers is that the servomotor drivers are more accurate and have better torque control, although this particular company uses a servomotor driver that can produce a torque range of .007 Nm- 5 Nm, which is significantly lower than the torque we aim to produce. However, though the torque output is much lower and this robot requires aid from humans, this type of existing product has similarities to what we ultimately plan to design, as it has different "screw feeder systems available which can be changed in less than five minutes. . . " and it has demonstrated a robot repeatable accuracy of +/- .01 mm[7]. This product is a solid starting point for the product our team will ultimately design, as it has some features that can be applied to our customer's needs, although we will be creating a more advanced product that has a much greater torque range and that will be independent from most human interaction while it performs its mechanical operations.

Another existing product is an electric screwdriver that is made by Mountz, a torque tool specialist. This company produces many different models that come in various sizes and produce various torques, and a beneficial feature is that the tool ensures accuracy with the fastening of bolts by having a shut-off clutch when a certain, predefined torque is set and achieved. The CL850AXH model produces the most torque, though it is at a much lower torque of about 4.5N m than our desired 100N m. However, by altering the speeds of rotation as well as other design parameters, a higher torque should be achievable.

It is important to note that most screwdrivers operate at a much lower range than 100N m, as most operate at a torque of less than 6 Nm, so this will be one very important design consideration to alter[8]. The CL850AXH only weighs about 1.7 kg, which is well under the desired 3.6 kg and this is a pro because something of this weight would give us room to add weight via the addition of a camera or other sensor which we would like to add onto our design.

Figure 4.2: Design of Tool Head by Mountz for M5 bolt[9]

This tool head has a front mounting flange, which is essential for a design like ours, since as long as the flange can be attached and detached simply, we could alter the kinds of applications or even simply the sizes of the bolts that the robot would be unscrewing, and we could similarly attach the flange to a handle for when it is to be used by a human. The design of such a tool head is shown to the right in Figure 3.

Additionally, there is another product on the market made by ASG-Jergens, and it is an electric screwdriver called the ASG-SD2500-50FX. This model is part of their SD2500 Series of screwdrivers and nutrunners, and it is again one of the higher producing torque electric screwdrivers that currently exist on the market, though that means it only produces about 5.6N m of torque. However, this product is desirable for the scope of the project because it has “transducerized torque and angle control” and it is very light as it weighs only 0.49kg[10].

This screwdriver is a DC electric tool and can be driven by a push start, i.e. as a human would do, or by a remote start operation, as a robot would use. The con is that this tool would need to increase its torque range, and we would also have to acquire a tool adaptor that would connect the tool to the robot as well as make the necessary signal connections. However, the functionality of a tool head designed in this way is certainly a pro, as it is already capable of being handled by either a robot or a human, and it is within our weight requirements. The appearance of such an electric screwdriver is depicted in Figure 4.

Figure 4.3: Design of Electric Screwdriver Tool Head by ASG [10]

Finally, a brief patent search has also been conducted for all parts of the product. Generally speaking, most patents that are related to the arm of the robot was filed back in the 80s and 90s, and therefore, have expired. Some patents that focus on the end effector, especially the mounting of the end effector, have only been filed in the past 10 years, as there were many research being done in the field. A table of patent search results can be found in Appendix E. The team has focused on a search of active patents, however, some of the expired patents are also listed to indicate technologies that can be used without charge.

5

Concept generation and selection

This chapter details the concepts generated for the different parts of the overall product at the planning stage of the project. There are four design concept sketches for the tool, accompanied by advantages and disadvantages for each design. Additionally, various factors were analyzed and explained in detail for the various software modules, embedded systems, and drive systems that the team is considering at this stage in the project.

5.1 Engineering specifications

The initial target values established for the final prototype are outlined in Appendix A. These values stem from the customer's needs and requirements, which were relayed to us in a meeting with our sponsor, as many engineering specifications rely on the customer needs, such as how the bolts upon which timing requirements are based are M18 bolts, and that the torque requested is 100 N m clockwise and 150 N m counter-clockwise. Apart from these, additional requirements were set for regulatory compliance and general usability of the end product. The target specifications consists of two parts: requirements that must be met and requirements that are desirable.

5.2 Design Concepts

The design concepts for the tool are based on the engineering specification as detailed in appendix A, as well as the advantages and disadvantages of existing tools similar to what we will be building that are already on the market. The final design must ensure that the tool meets at a minimum all of the requirements listed in appendix A. It is especially important to note that the sponsor would greatly appreciate some sort of sensor on the tool head that would aid the robot in sensing its environment so that it can orient itself and compensate positioning tolerances in a similar way as humans do. Additional goals are that the design of the tool head will weigh as little as possible, be as ergonomic as possible, be as quiet as possible, and have a modular design with one main part that has the ability to connect to different tool heads with ease.

5.2.1 Design Concept 1

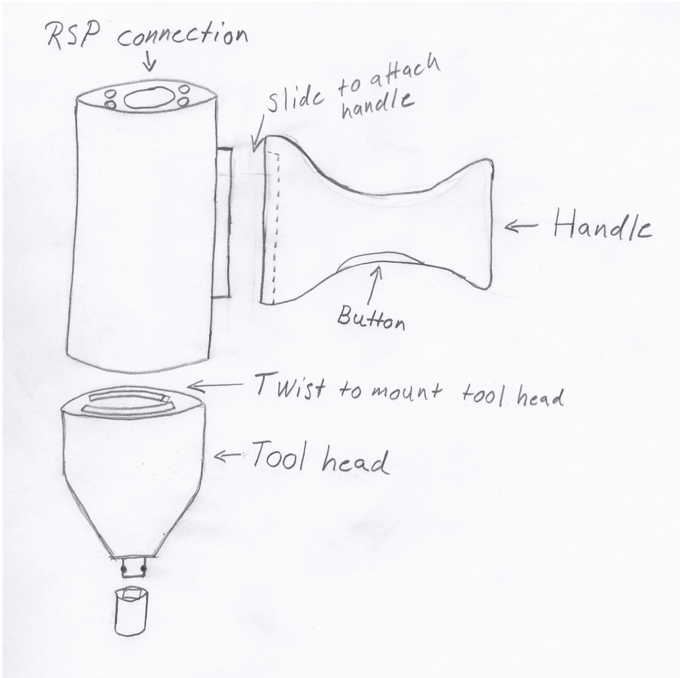


Figure 5.1: Concept 1 of the tool design

The concept found in Figure 5.1 consists of three major parts; the tool head, the handle and the tool body. The handle is mounted using slotted slides found on the tool body with a corresponding counterpart on the handle. When the tool is being used by a robot, the handle can easily be dismounted in order to not disturb the robot's movement. The tool head can also be easily dismounted by using a twist motion to seperate the tool head from the tool body.

Advantages

The attachable handle enables an operator to have a very familiar and intuitive interaction with the tool, whilst not being in the way for the robot's movement since it is then dismounted from the tool. When the tool is used by a robot, it is connected mechanically to the RSP interface on top of the tool.

Disadvantages

However, this concept puts high demands on the mechanical interfaces (the slotted slides and the twist motion for the tool head) due to the fact that the tool delivers high torque and thereby strains on the interfaces. Furthermore, it requires a smart electrical interface between the handle and the tool body in order to transfer the start signal from the handle to the computer which controls the motor.

5.2.2 Design Concept 2

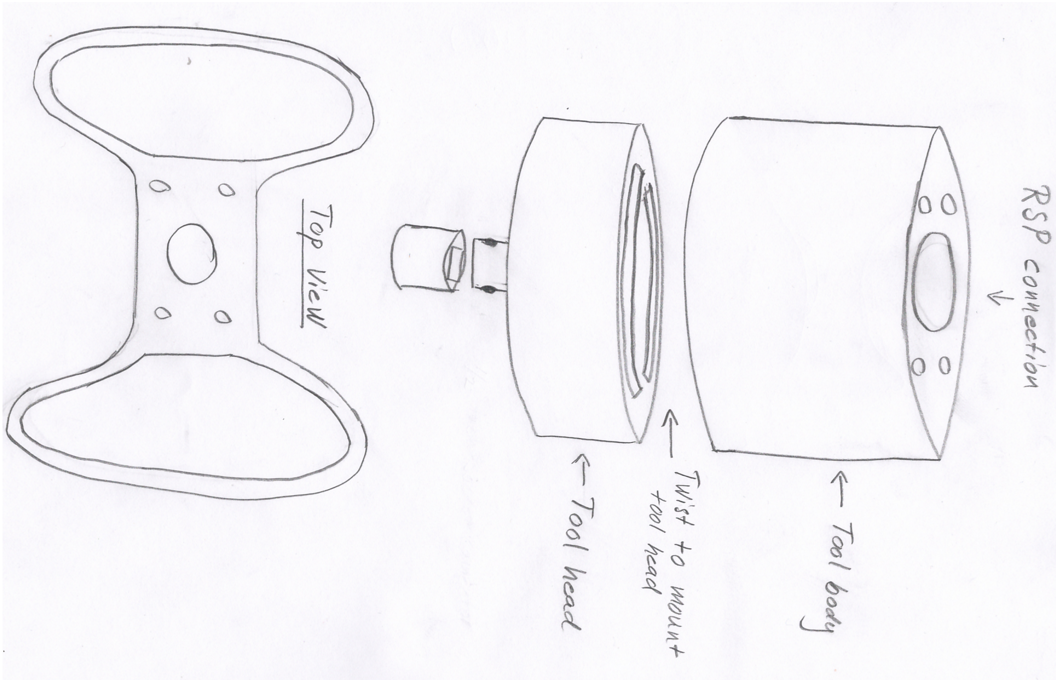


Figure 5.2: Concept 2 of the tool design

In this concept, found in Figure 5.2, the tool consists of three parts, similar to the previous design concept. However this concept uses the RSP connection for both the robot and the operator. When used by a human operator, the tool would be mounted on a two handed handle which enables the operator to have a steady hold of the tool.

Advantages

The two tool parts for this concept have a larger diameter, allowing the tool to be shorter in length and also allowing a larger motor and possibly battery to be mounted in the tool body section. The shorter length of the tool could improve the robot's ability to navigate and have a better reach for the mounting operation in difficult angles.

Disadvantages

The cons with this concept is that having the same RSP interface for the two handed handle and the tool head becomes demanding since designing and manufacturing the handle could be quite complex, both because of its size and also the integration of the RSP connection. This concept can also lead to longer mount/demount time when assembling the tool and handle.

5.2.3 Design Concept 3

Design concept 3, found in Figure 5.3, builds on the same idea as design concept 1, but adds a hinge in order for the tool to be used both as a torquewrench and a traditional pistol-shaped nutrunner by human operators. The hinge is spring-loaded in order for the robot to be able to return it to a straight position with a signal before picking it up. This adds demands on the holder for the tool when it is not used, as the tool must be able to straighten itself without falling off of the holder. The main unit uses the same twist-to-connect mechanism for the tool heads as design concept 1. The buttons for starting the tool are located so that they can be reached ergonomically both when using the tool straight and bent, and multiple buttons enable forcing the operator to use both hands for added safety. The tool heads can have the option for an electromagnet in the socket connector, to enable the robot operator to pick up rotational elements by itself.

Advantages

The advantages for this design include that there is added flexibility to use the same tool in different kinds of operations, where different tool shapes are required, and also that no parts must be disassembled when switching from the human operator to the robot operator.

Disadvantages

The main con for this design is that it contains more parts and joints than the previous design concepts, which adds complexity, and might negatively impact reliability.

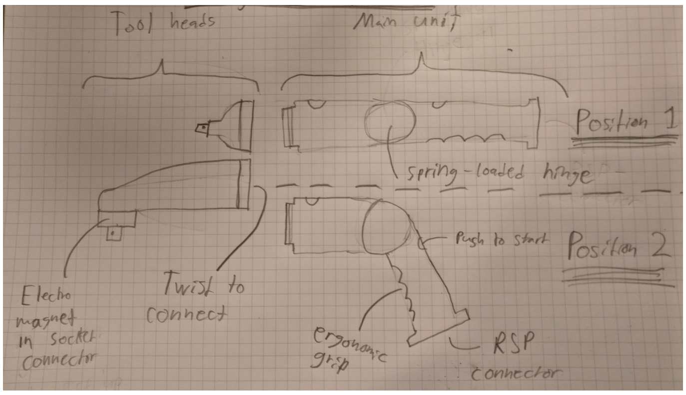


Figure 5.3: Concept 3 of the tool design

5.2.4 Design Concept 4

The concept found in Figure 5.4 below is similar to the above-mentioned design concepts 1 and 3. This concept also contains an ergonomic design for both humans and robots because there is no handle to get in the way when the robot is using the tool, yet there is a strong hand grip embedded on the base so that when it is detached from the interface, the human can easily control the motions of the tool without the tool slipping from his or her hand. Instead of having a twist-on-twist-off connection between the tool head and the base, it has a push-release button, where the tool head is linked into the base by popping it into the appropriate grooves on the tool adapter, and then is locked in place until the button is pushed to release the tool head so that another can be loaded on. This way different types of tool heads can still be mounted via a 1/2 inch socket connector with various sized screw-driver/torque wrench heads on the other end.

Advantages

The design does not incorporate a handle, which would add weight and make movements more restricted for the robot. Yet, it has a narrow section with grips so that the human will not have trouble controlling it. Additionally, there should not be as many strains between the tool adapter and interfaces as instead of a twisting motion which will induce wear on the surfaces, there is a lock-in-place and push button connection which will not cause as much friction between the surfaces.

Disadvantages

However, this concept is more complex to manufacture because the slots for the lock-in-place feature will have to be in a certain place and the exact corresponding measurements must be manufactured onto the tool heads to ensure the system is indeed locked in as strongly as it should be to ensure the tool does not come apart while performing its high torque operations. And, if it is more complex to create that means it will almost certainly be more expensive.

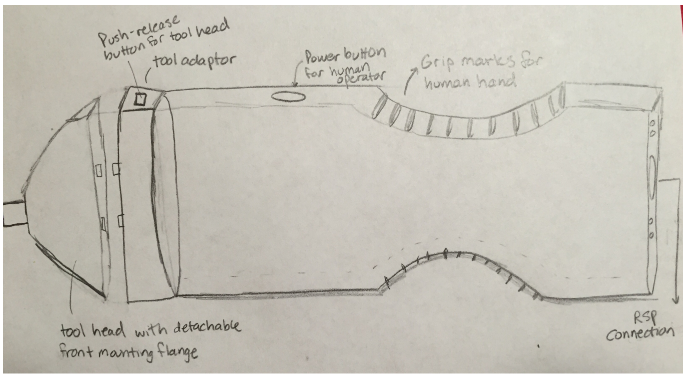


Figure 5.4: Concept 4 of the tool design

5.3 Software

A requirement for the project is that the tool must communicate with an overhead system using ROS[11], a framework providing communication protocols for exchanging data between nodes, independent of what machine the node is running on. The framework also contains packages for computer vision and various other robotics utilities. ROS in itself promotes modular design of software, hence this will be embraced to the largest possible extent in the development.

By recommendation by the Open Source Robotics Foundation[12], the coding will be done in python, following the ROS python coding standards to the largest possible extent, and also searching for existing packages we can use within the ROS project. The development method will be based on unit tests, which are recommended and required by the Open Source Robotics Foundation in order to publish packages to the ROS repositories[13], but also in order to code in an organised manner. The modular design and ROS framwork will enable extensive data harvesting opportunities to be added to be utilized in the overhead system. The requirements on the software are listed in Table 5.1 are based on the requirements of the complete tool.

Table 5.1: Requirements for software

No.	Requirements for software
1	Communicate between tool and overhead system with operation setting
2	Provide drivers for connected hardware, such as drive system and sensors
3	Contain control algorithms to ensure that the right speed and torque are areachieved
4	Protect critical components from overload
5	Communicate basic signals to operator, such as finished and error
6	Be able to provide overhead system with positioning guides based on sensorinput

5.4 Embedded system

Since the goal of the project is a functional prototype, the embedded system will be a finished microcontroller board instead of a custom PCB, in order to focus on distinguishing features instead of PCB design. The requirements for the embedded system are listed below in Table 5.1 ,which were decided based on the requirements for the complete tool.

Table 5.2: Requirements for embedded system

No.	Requirments for embedded system
1	Be a finished microcontroller board
2	Be able to take advantage of ROS communication protocol
3	Have the outputs required to control drive system
4	Have the inputs required to interpret sensor data
5	Be able to connect a network peripheral
6	Be able to do signal processing for advanced sensors (camera, radar, etc.)
7	Have a small form factor to enable freedom in mechanical design of tool

Based on the above requirements and a search of boards available on the market, the following suggestions would be good choice to fulfill the requirements. The general advantages and disadvantages for each suggested board are lists for the concept selection process in the future.

5.4.1 Raspberry Pi

The raspberry pi zero[14] is a microcontroller board featuring a 1GHz processor and 512 Mb of RAM, as well as a 40pin header and micro usb connectivity. Advantages and disadvantages based on our above requirements are listed in the following Table 5.3.

Table 5.3: Advantages and disadvantages for Raspberry Pi

Advantages	
1	Runs the full ROS framework on top of debian
2	Capable of processing more complex signals such as image/video
3	Some model has built-in Wi-Fi module (Raspberry Pi 3)
4	Has plenty of spare capacity for expanding software at a later stage
5	Has small form factor
Disadvantages	
1	Has only one PWM output
2	Has no A/D converter connected to GPIO

5.4.2 Arduino MKRZero

The Arduino MKRZero features a 48MHz processor and 256 kB of flash memory, as well as numerous input/output pins with different capabilities. Advantages and disadvantages based on our above requirements are listed in the following Table 5.4.

Table 5.4: Advantages and disadvantages for Arduino

Advantages	
1	Has twelve PWM output pins
2	Has one analog input pin
3	Has predictable (linear) processing
4	Has small form factor
Disadvantages	
1	Has no full operating system, only runs ROS communication protocol[15]
2	Not capable of processing of complex signals, such as image/video

5.5 Drive system

Based on the general requirements for the complete tool, the drive system will meet the following requirements.

Table 5.5: Drive system requirements

Must have	
1	able to deliver a torque of 60N m
2	have a top speed of at least 400 rpm
3	be able to mount 8 M18 bolts, 10 seconds in between, 50 times per 8h, evenly spread over the day
4	be able to operate in a temperature span of 5-40 degrees celcius
5	have a cordless power supply
Should have	
1	be as light as possible
2	have a noise level of less than 55dB
3	not convey vibrations larger than 5
4	be able to deliver a torque of 100Nm clockwise and 150Nm counter-clockwise
5	have a service life of at least 3000 hours

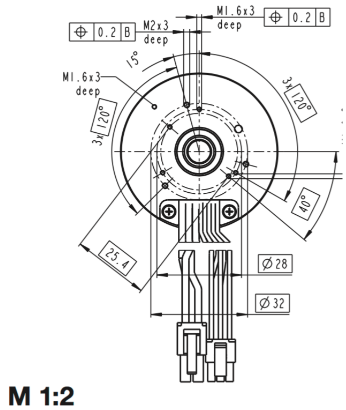
5.5.1 Motor

There are different kinds of options when it comes to motors. Depending on what design the team will pursue, different motors are suitable. In order for the tool to fulfill the speed requirement, the system should be able to deliver a speed of at least 400 rpm. One important aspect is that the tool does not need to be able to produce this speed throughout the whole cycle. Right before the screw is about to get completely entered, the speed will not be that high. Instead, the voltage could be increased to deliver increased torque. The maximum torque is only required during a short time and an electric motor handles this short increase of voltage without getting damaged, provided sufficient cooling. The type of motor considered is brushless DC, for several reasons. Brushless DC motors provide a large power to weight ratio[16], which will help fulfill several requirements, and have longer service life and less need for maintenance. Due to the fact that there is no physical connection between the stator and rotor, the rotor can be sealed off, protecting it from harsh and dirty environments. However, bldc motors demand more electronics in order to run.

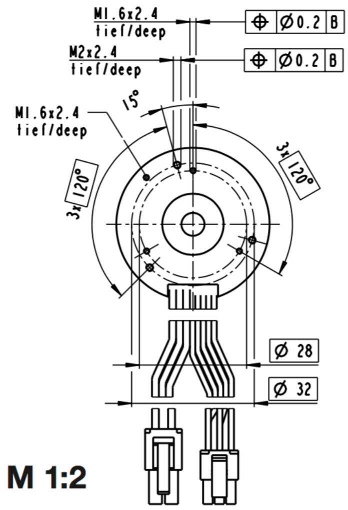
One motor that could fulfill the requirements is the Maxon EC-i 52, brushless, 180 W, 24 V [17]. With a gear which could increase the torque tenfold and therefore lessen the rotational speed tenfold, this choice would be suitable for the prototype. This motor is shown in Figure 9 (a). Another option could be the Maxon EC-i 40 brushless, 100 W, 48 V [18]. This one does not fulfill the requirements regarding torque, but as mentionend earlier, the electric motor should be able to withstand an increased voltage during a short while which also would increase the performance. This motor is pictured in Figure 9 (b).

Figure 5.5: EC-i series brushless motor

(a) ECi52



(b) ECi40



In order for the required torque to be met, the proposed motors must deliver a high torque. Another solution could be to use a less powerful motor and exploit a lever combined with the robot or operator's motion and get the correct torque out of that. This will be considered in the future when it comes to the more refined concept generation.

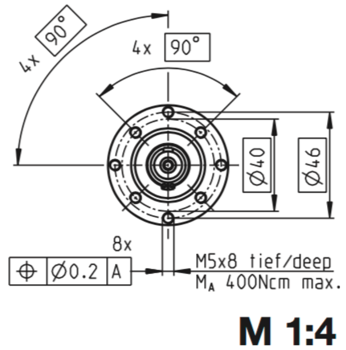
5.5.2 Gear

It is difficult to find an electric motor which could reach the high torque needed. A gear must therefore be used and the group has looked at a few different options. The following gears are compatible with the suggested motors above and have a ratio that fulfill the speed requirement as well.
An option is the Planetary Gearhead GP 52 C which specifically is compatible with

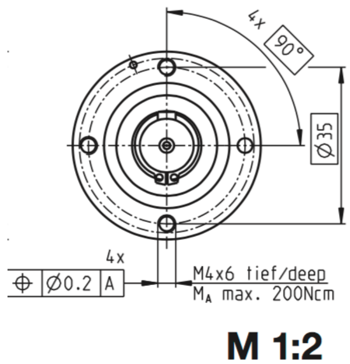
the EC-i 52 electric motor [19]. This option is pictured in figure 5.5(a). Another alternative is the Planetary Gearhead GP 42 C which suits the alternative EC-i 40 [20]. This option is pictured in Figure 5.6 (b).

Figure 5.6: GP series gearbox

(a) Planetary Gearhead GP 52 C



(b) Planetary Gearhead GP 42 C



5.5.3 Battery

As previously mentioned, the tool should be wireless, and therefore, a solution to the energy supply is to use a battery coupled with wireless charging, alternatively connectors in the tool bed and in the robot interface. What kind of battery to use is of less importance than capacity and weight. In order for convenient use, the battery should be rechargeable and the battery should charge quickly due to the requirements (see appendix A). In order to decide the optimal capacity of the battery, an entire workday is to be simulated in Simulink.

5.6 Concept Selection

In order to decide which components and tool part designs best met the customer needs, various Pugh Concept Scoring tables were developed which show how the customers needs were weighed and how the final design choices were decided upon for the ultimate 3D prototype.

5.6.1 Concept Scoring Charts for Tool Design

This section contains the concept screening process for the design of the tool, which is made up of two handles and a tool head which are all connected to a tool body. The design concepts were sketched and described in Section 5.2, and the various ways that the parts were connected and designed were taken into consideration with the customer needs for the final design chosen for the prototype. The Pugh Concept Scoring chart was used, and is shown in Figure 5.7.

Furthermore, once the general design concept was chosen, two 3D models were created based on the general design concept chosen, namely design concept 1, and then these models were weighed against each other as well as various design and functionality based customer needs. Images of both of these 3D modeled concepts can be found in Appendix B, specifically, 3D model concept 2 (which was not selected) is depicted by figures B.8, B.9, and B.12, and the aspects of 3D Model Concept 1 is depicted by all other figures in that section. Another Pugh Concept Scoring chart was used for this second evaluation, and is shown in Figure 5.8.

Figure 5.7: Pugh Concept Scoring for Tool Design

		Concepts							
		Design Concept 1		Design Concept 2		Design Concept 3		Design Concept 4	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Safe	0.21	3	0.63	3	0.63	2	0.42	3	0.63
Ease of Use	0.13	4	0.52	3	0.39	3	0.39	4	0.52
Ease of Mfg.	0.13	4	0.52	3	0.39	2	0.26	1	0.13
Cost	0.05	3	0.15	3	0.15	2	0.10	3	0.15
Efficient	0.2	3	0.60	3	0.60	4	0.80	3	0.60
Durable	0.13	3	0.39	3	0.39	3	0.39	3	0.39
Portable	0.08	3	0.24	3	0.24	3	0.24	3	0.24
Ergonomic for human user	0.15	5	0.75	3	0.45	4	0.60	2	0.30
Ergonomic for robot	0.15	3	0.45	3	0.45	3	0.45	3	0.45
	Total Score		4.25		3.69		3.65		3.41
	Rank	1		2		3		4	
	Continue	Yes - Primary		No		No		No	

Relative Performance	Rating
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

As depicted in Figure 5.7, design concept from Section 5.2.1 was the only design choice chosen to be continued. The total ranking was clearly much higher than the other three design concepts, and this is largely in part because it will be easier to manufacture, and easier to use by humans compared to the other concepts. Furthermore, though the reference concept, design concept 2 from Section 5.2.2, scored the second highest, the ease of use by a human user was an essential part to the customer needs; and, since concept 1 was declared the most desirable by the sponsor specifically for this reason, it seemed plausible that the much higher score for design concept 1 outweighed the consideration of considering design concept 2 as even an alternate choice. Finally, design concept 3 from Section 5.2.3 and concept 4 from Section 5.2.4 were both eliminated as choices primarily because concept 3 would be too difficult to 3D print and assemble and concept 4 would similarly be too difficult to 3D print, and it would also be more difficult to use by a human than the other choices. It is important to note that though concept 1 was chosen, the final design will include a second handle positioned at a 90 degree angle from the first, as that was suggested by both the sponsor and current manufacturing workers at Volvo Trucks.

Figure 5.8: Pugh Concept Scoring for 3D Modeling of Tool Design

		Concepts			
		3D Model Concept 1		3D Model Concept 2	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score
Safe	0.21	3	0.63	3	0.63
Ease of Use	0.20	4	0.80	3	0.60
Ease of 3D Printing	0.18	3	0.55	4	0.72
Aesthetically Appealing	0.10	5	0.50	2	0.20
Ease of Assembling Handle	0.12	4	0.48	3	0.36
Ease of Assembling Tool Head	0.12	3	0.36	3	0.36
Efficient	0.2	3	0.60	3	0.60
Durable	0.13	3	0.39	3	0.39
Portable	0.08	3	0.24	2	0.16
Ergonomic for human user	0.20	4	0.80	3	0.60
Ergonomic for robot	0.20	3	0.60	3	0.60
	Total Score		5.95		5.22
	Rank	1		2	
	Continue	Yes - Primary		No	

Relative Performance	Rating
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

As depicted in Figure 5.8, 3D Model Concept 1 was chosen based on various factors. One of the biggest advantages Concept 1 had over Concept 2 is that it is expected to be easier for the human to use, as it is less bulky, and also the handle assembly is expected to be easier, since it uses a slide-in interface instead of having to be screwed on, as was the case for design concept 2. Additionally, design concept 1 is more aesthetically pleasing without losing functionality, and it should be a bit more portable thanks to its smaller size. Based on these differences, design concept 1 was chosen to be continued for the design of the final working 3D prototype, and therefore, it is described in much more detail in Section 7.

5.6.2 Concept Scoring Charts for Drive System

Figure 5.9: Pugh Concept Scoring for Drive System

Concept selection					
		Impact driver		Reduction gear	
Selection criteria	Weight	Rating	Weighted Score	Rating	Weighted score
Maximum torque	0.3	5	1.5	3	0.9
Power draw	0.2	3	0.6	3	0.6
Rotational speed	0.2	5	1	2	0.4
Reliability	0.2	3	0.6	5	1
noise	0.05	1	0.05	5	0.25
weight	0.05	3	0.15	3	0.15
	Total:	3.9		3.3	
	Rank:	1		2	
	Continue:	Yes		No	

Relative Performance:	**Rating:**
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

The team has found two main solutions for the high torque drive system, one is an impact drive design and the other one is a reduction gear design. After comparing the two through weighted ratings across multiple criteria, the team decided to continue with impact drive design. Criteria the team took into consideration includes: maximum torque available, power draw, rotational speed, reliability, noise, and weight. Each solution was given a rating for each criterion where 5 is the most desirable rating and 1 is the least desirable rating. The impact driver got a rating significantly higher than the reduction gear design in maximum torque and rotational speed, which contributed to its overall higher score. The reduction gear design received a higher score in reliability and noise level, but since those criteria have lower weights, it is not enough to combat the higher weighted torque and speed.

5.6.3 Concept Scoring Matrix for Embedded System

A Pugh scoring matrix was used in order to select the best suited embedded system, which is shown below, in figure 5.10

Figure 5.10: Pugh Concept Scoring for Embedded System

Concept Scoring Matrix for Embedded System					
		Raspberry Pi Zero W		Arduino MKRZero	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score
Image Processing	0.3	5	1.5	1	0.3
ROS Compatibility	0.3	5	1.5	3	0.9
Real-time Performance	0.2	2	0.4	5	1
Hardware Performance	0.1	4	0.4	3	0.3
Size	0.05	5	0.25	5	0.25
Power Consumption	0.05	5	0.25	5	0.25
	Total		4.3		3
	Rank	1		2	
	Continue	Yes		No	

Relative Performance	Rating
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

As described in Section 5.4, the team chose two solutions for the embedded system to compare, Raspberry Pi Zero or Arduino MKRZero. After a concept scoring process, the Raspberry Pi was selected to be the embedded system solution. As shown in Figure 5.10, these two solutions are rated with 6 selection criteria. The most important criteria are the image processing ability, the ability to run ROS, and the ability to do real-time control. Raspberry Pi is much more powerful to do image processing compared to Arduino. In addition, Raspberry Pi is able to run the full version of ROS. These two advantages are the main reason that Raspberry Pi gets a higher score in the concept scoring process. However, the Raspberry has poor real-time performance. Some solutions to this problem are listed in Section 7.4.5. If a real-time controller is found to be needed in the future, an Arduino can be easily added to the system.

6

System level design

In this chapter the overall system level design is displayed and the product structure explained. A more detailed and in-depth explanation of the components is found in section 7.4.

As shown in Figure 6.1 the tool consists of three major parts, the tool body, the tool head and the handles. These parts consist of both mechanical and electrical components. The product structure is created based on the customer needs which were given to the team by the sponsor.

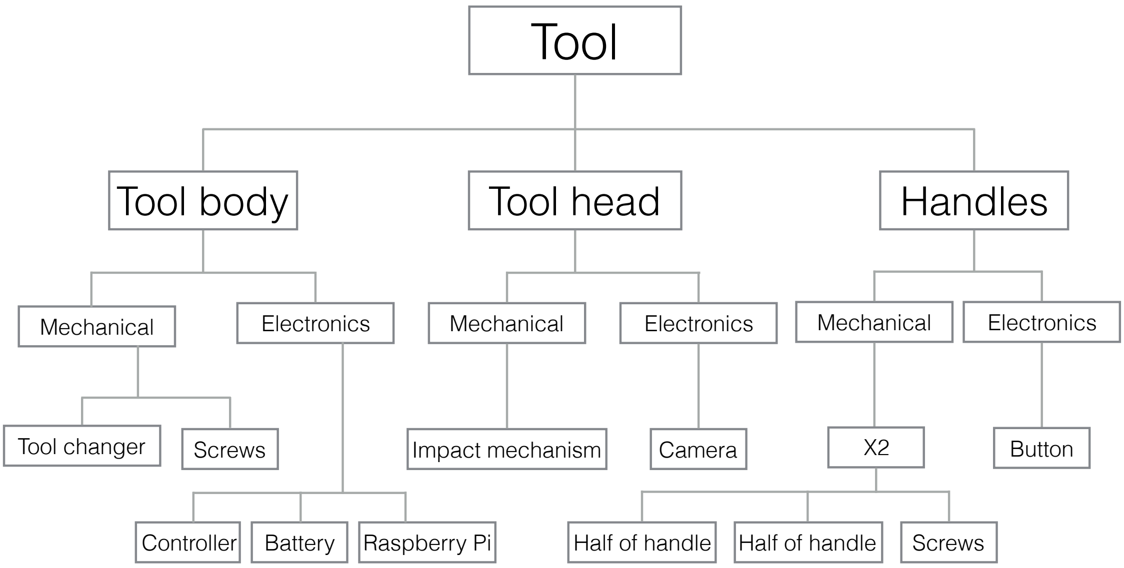


Figure 6.1: A schematic system level design

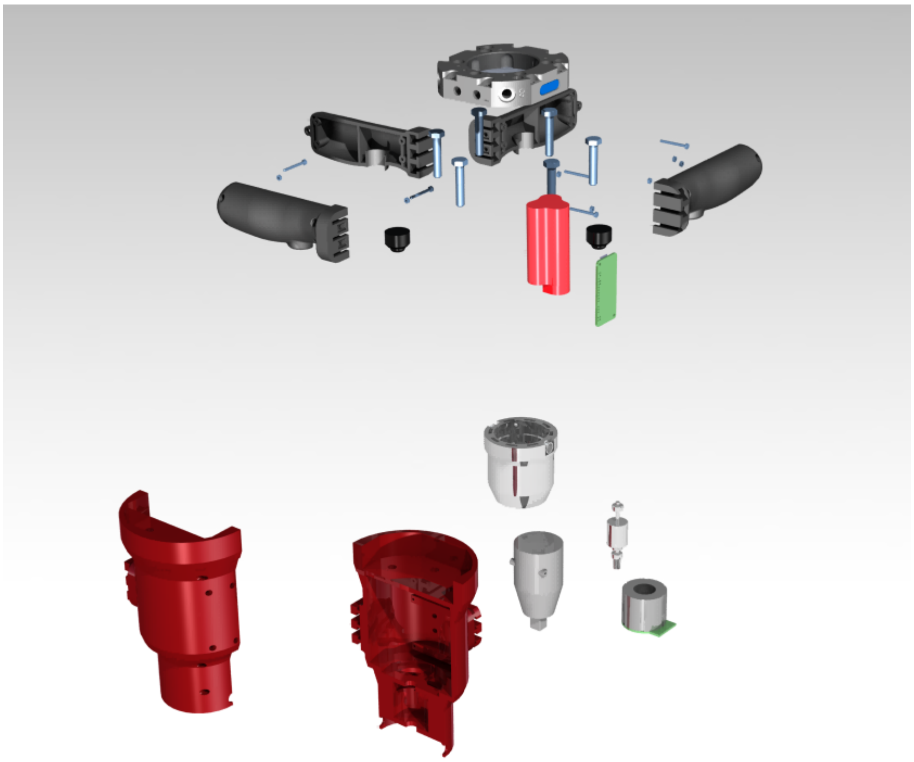


Figure 6.2: An exploded view of the assembly

The primary way of connecting the various parts together is by using screws, which applies to assembling the handles, the tool body and mounting the tool changer. Screws have been chosen in order to get a secure, rigid and tight joining between the different parts. As shown in Figure 6.2 the tool body and the handles are made up out of two halves which require a secure joining, and hence using screws was the best option.

The handles mount to the tool body using slots which enables a quick and easy mounting/demounting. This interface was chosen in order to get a hassle free and simple mounting operation. By using this kind of slide-in interface, there is no need to keep track of screws in order to mount a handle, and since this mounting/demounting operation could occur often, this feature is seen as a big advantage.

The electrical part of the system consists of two main parts: a raspberry pi and a maxon motor brushless-dc motor controller. The raspberry pi is used for wireless communication with the overhead system using ROS, and changing the speed setpoint values of the motor controller based on speed and current readings. The raspberry pi can also be used for processing data from complex sensors such as cameras.

7

Detailed Design

7.1 Manufacturing process plan

A manufacturing process plan, shown in Table 7.1, was developed for the parts of the tool that must be created, as well as how the inner components, such as the motor, battery and circuit boards, will be assembeled into the tool body.

As this is a prototype, the manufacturing process used will be 3D printing which enables for a simple and relatively quick manufacturing of the product. This process is applicable for low volume production, is very versatile, and doesn't require a high level of competence within manufacturing. Moreover, it provides the ability to detect flaws and visualize the designed concept within the early stages of the design process. 3D printing also reduces the cost associated with prototypes significantly compared to other methods, as the cost of material is free, and the necessity of hiring a third party company to manufacture the parts is eliminated [21].

However, for a final, high volume production product, 3D printing is not a preferred choice due to its lack of scalability to high volume production. The process then becomes time-ineffective and costly. The process is also limited to certain materials which may not have sufficient strength for the end consumer [21].

In table 7.1 the manufacturing plan for a prototype of the tool is stated. Please see Appendix B for all figures mentioned within the table.

Table 7.1: Manufacturing Process Plan

Assembly name	**Material type**	**Operations**
Tool body	ABS	3D Print
		Assemble using thread tap and screws
Tool head	ABS	3D Print
		Assemble using thread tap and screws
Handle	ABS	3D Print
		Assemble using thread tap and screws
Final Assembly of tool parts		
Two halves of tool body	ABS	The two halves of the tool body will be screwed together using M3 bolts
Handles to tool body	ABS	The handles will mount to the tool body using slots for an easy and fast mount/demounting operation. Images showing this interface is found in Figure B.15.
RSP connector to tool body	ABS	The RSP female part will be attached to the tool body via (6) M8 bolts. Renderings of the tool changer and how it connects between the tool and the robot can be found in figure B.13 and B.14.
Tool Head to tool body	ABS	The tool head will be mounted to the tool body via M3 bolts. The team will test the minimum amount of bolts necessary for a secure enough attachment. Figure B.4 depicts this piece.
Inner components to tool body	ABS, hot glue	The motor, impact assembly, and battery will be mounted to the tool body via M3 bolts, and the sensors will be mounted to the tool head via a hot-glue gun.

7.2 Analysis

A simulink model of the impact drive was developed in order to calculate the energy consumption as well as to better understand the dynamics of the system and heat production, based on the work of S. Zhang and J. Tang [22]. The resulting block schematic can be seen in Figure (7.1). The system consists of five subsystems, as detailed in Table (7.2).

Table 7.2: Simulink model subsystems description

Subsystem	Description
motor_mechanical	Conversion from voltage to speed and torque depending on load.
motor_heat	Heat transfer from winding to surrounding air.
spring	Motor charging impact driver spring.
hammer	Spring acceleration of hammer.
anvil	The hammer hits the anvil which results in reaction torque as the anvil retards the hammer.

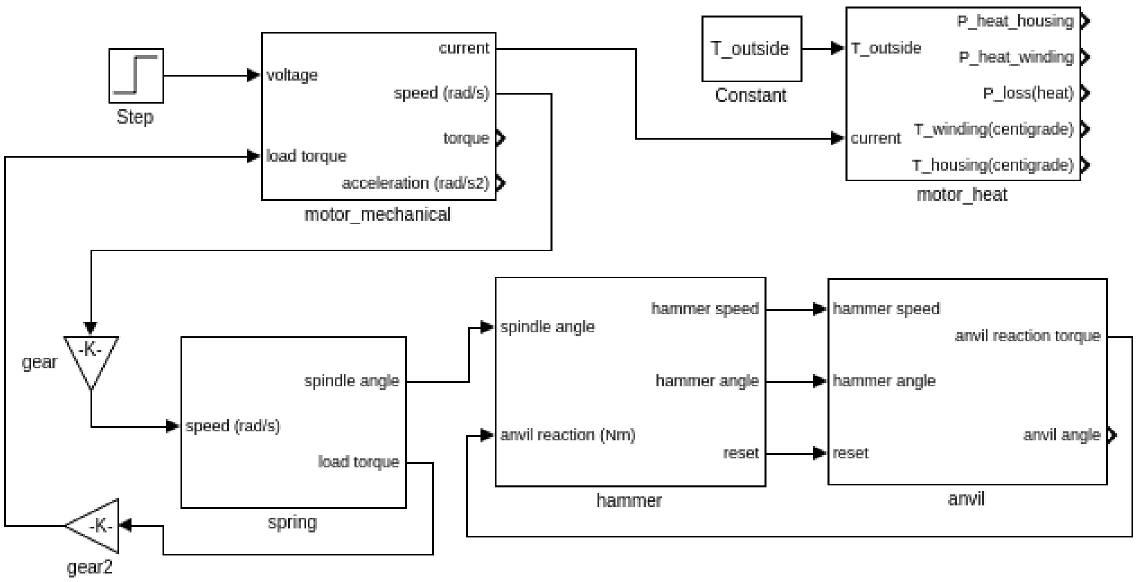


Figure 7.1: Impact drive simulink schematic

7.2.1 Battery capacity need simulation results

The battery size requirement for the tool was determined using the model detailed in sections 7.2.2 onwards. The simulation is run over an hour of the work cycle detailed in the customer, which means entering eight 80mm M18 bolts with ten seconds in between 50 times evenly spread over eight hours, meaning six cycles per hour. The simulation was run at max voltage, resulting in more than 200 impacts on each bolt after it was entered. This, of course, is a lot more than would happen in normal assembly use, but was kept due to simplicity and to see what the battery

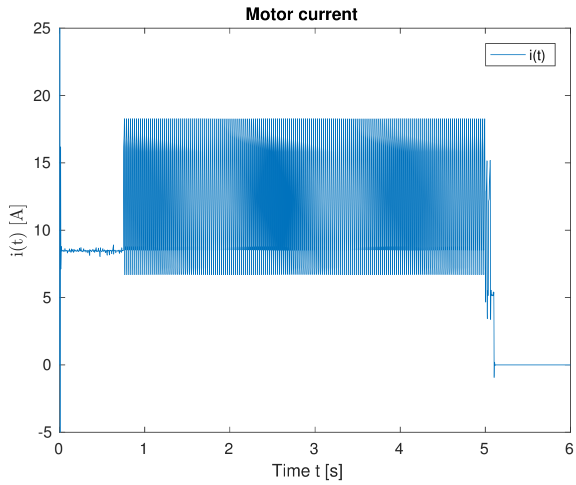


Figure 7.2: Current draw during mounting of one M18 bolt

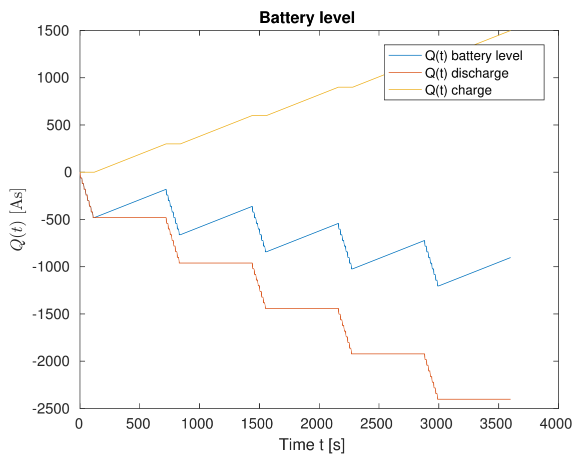


Figure 7.3: Battery level, discharge and charge (500mA) during one hour of work

requirements would be under heavy use. Since the voltage is kept constant at 12 Volts and the battery voltage is also 12 volts, the energy is measured in Ampere-seconds(Coulomb), which is a common unit for measuring battery size. A graph of the current drawn during the course of mounting one M18 bolt can be found in figure (7.2), where the period when impacting is simulated is seen clearly as the current fluctuates between 8 and 18 Amperes. The battery charge and discharge are plotted in figure (7.3). One work cycle drains 480 A s, which needs to be recharged in 600 seconds (the time before the next sequence). This gives us that the charger must supply $i_{charger} = \frac{480}{600} = 800$ mA. In the simulation, a charging current of 500 mA was used. Hence, if the entire battery capacity could be used, 480 A s would suffice. However, as the battery capacity decreases with each charge/discharge cycle, this is not the case. If, for example, 12% of the battery capacity is to be discharged each cycle, the original battery capacity needs to be 3600 A s. Therefore, the battery capacity is now determined by the desired servicing interval.

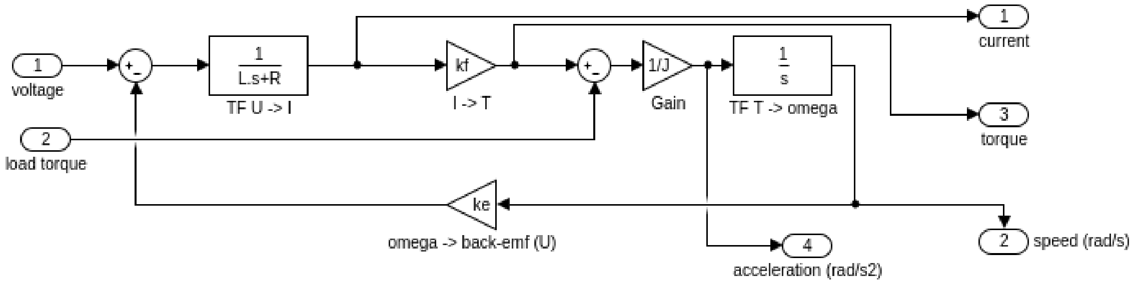


Figure 7.4: Impact drive motor electrical/mechanical schematic

7.2.2 Motor electric

The mechanical part of the motor is modeled with the equations

$$u(t) = Ri(t) + L_a \frac{di}{dt} + k_e \omega(t) \tag{7.1}$$

and

$$T_{dev} - T_{load} = J \frac{d\omega}{dt} \tag{7.2}$$

, where u(t) is the winding voltage in Volts, i(t) is the winding current in Amperes, R is the winding resistance in Ohms, L_a is the winding inductance in Henrys, $\omega(t)$ is the motor shaft speed in $\mathrm{rad\,s^{-1}}$ and k_e is the back emf constant in $\mathrm{V\,rad^{-1}\,s^{-1}}$. These equations were laplace transformed into the transfer functions

$$I(s) = (U(s) - k_e \Omega(s)) \frac{1}{R + sL_a} \tag{7.3}$$

and

$$\Omega(s) = (T_{dev} - T_{load}) \frac{1}{sJ} \tag{7.4}$$

. In simulink they are modeled as detailed in Figure (7.4).

7.2.3 Motor heat losses

Motor heat losses appear due to the resistance in the windings. The heat power developed in the windings is given by

$$P_{loss} = R_{winding} i^2_{winding} \tag{7.5}$$

. Where $R_{winding}$ is the resistance in the motor windings and $i_{winding}$ is the current in the windings. The heat transfer from the windings to the motor casing is given by

$$P_{wc} = h_{winding}(T_{winding} - T_{casing}) \tag{7.6}$$

, where P_{wc} is the heat power transfered from the winding to the casing, $h_{winding}$ is the transfer coefficient in $\mathrm{W\,K^{-1}}$, $T_{winding}$ is the winding temperature and T_{casing} is the motor shell temperature. The transfer of heat from the motor casing to the surrounding air is given by

$$P_{co} = h_{casing}(T_{casing} - T_{\infty}) \tag{7.7}$$

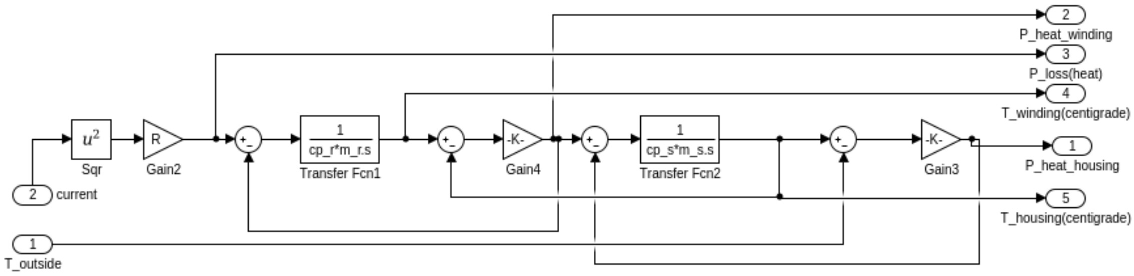


Figure 7.5: Impact drive motor heat development schematic

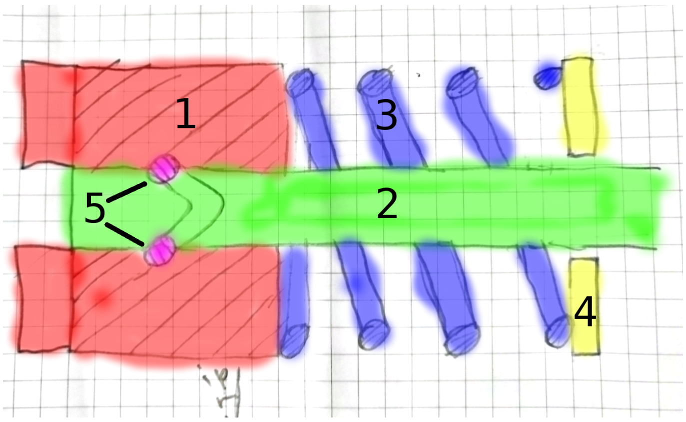


Figure 7.6: Impact drive spring-spindle-hammer schematic

, where P_{co} is the heat power transfered to the surrounding air, h_{casing} is the heat transfer coefficient between the casing and the air, and T_∞ is the temperature of the surrounding air. Equations (7.5), (7.6) and (7.7) were used in simulink as can be seen in figure (7.5).

7.2.4 Impact drive spring

The motor powers the impact drive on an input shaft with grooves cut into it, and and during half a revolution a spring is compressed in order to store the energy which will later be used to accelerate the hammer which delivers the impact. Hence, the impact mechanism was modeled as three separate, but connected, parts, as seen in Table (7.2). The mechanics of the spring and charging spindle are illustrated in Figure (7.6) and the parts are labeled in table (7.3).

Table 7.3: Description of parts in figure (7.6)

Part	Description
1	Hammer
2	Spindle
3	Spring
4	Tool body
5	Steel balls

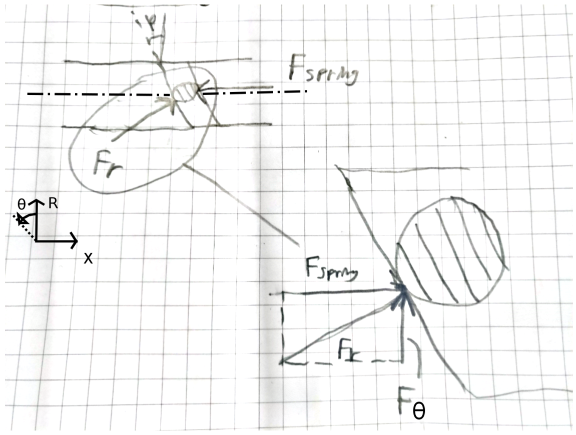


Figure 7.7: Spring reaction forces

The force from the spring is proportional to the spring compression as per

$$F_{spring} = k_{spring}x$$

, where x is the compression of the spring in meters, k_{spring} is the spring constant in $\mathrm{N\,m^{-1}}$ and F_{spring} is the spring force. The spring pushes the hammer, which in turn is connected to the input spindle with balls running in a v-groove in the spindle, as illustrated in figure (7.6). The reaction forces between the ball and the spring and input spindle are illustrated in Figure (7.7).
In order to achieve equillibrium, the x-component of reaction force F_r must equal the force the spring applies, F_{spring}. Hence,

$$F_r = \sin(\varphi)F_{spring}$$

and

$$F_\theta = \tan(\varphi)F_{spring}$$

, where ϕ is the slope of the groove relative to the r-axle in radians, F_r is the reaction force on the ball from the spindle, and F_θ is the θ-component of F_r. Then, the resulting torque on the spindle caused by the spring is simply

$$T_{load}(x) = rF_\theta = r\tan(\varphi)k_{spring}x$$

, where T_{load} is the reaction torque on the spindle caused by the spring compression x, as illustrated in figure (7.8). The spring compression depends on the spindle angle according to

$$x = \tan(\varphi)r\theta$$

for $0 \leq \theta \leq \pi$, where θ is the angle in radians from where the spring is the least compressed. If the spring already has a compression d when the hammer is in the leftmost position, the torque function becomes

$$T_{load}(\theta) = r^2\tan^2(\varphi)k_{spring}\theta + k_{spring}d \tag{7.8}$$

. This function was implemented in simulink to calculate the load torque on the motor when charging the spring as seen in figure (7.9), together with switches for resetting integrators at certain angles in order to make the behavior periodic.

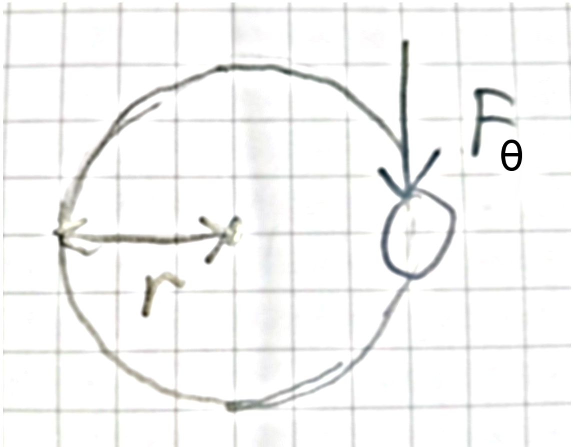


Figure 7.8: Spindle reaction torque

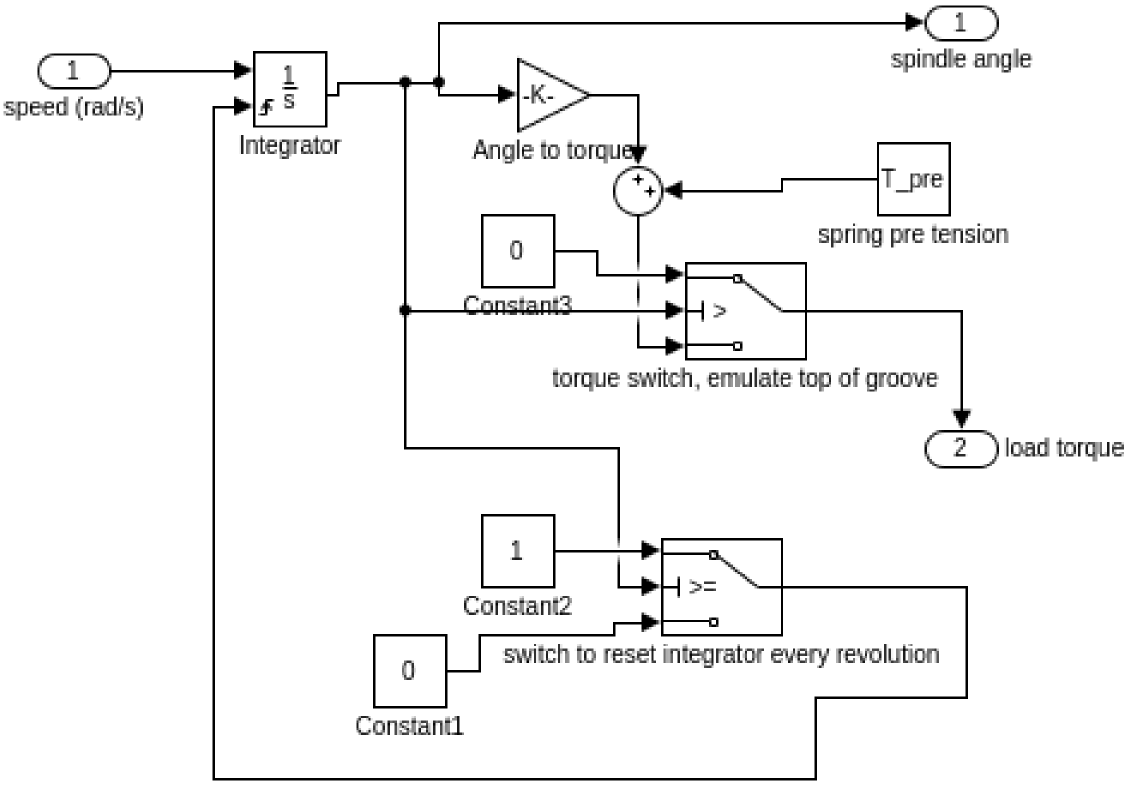


Figure 7.9: Impact drive spring schematic

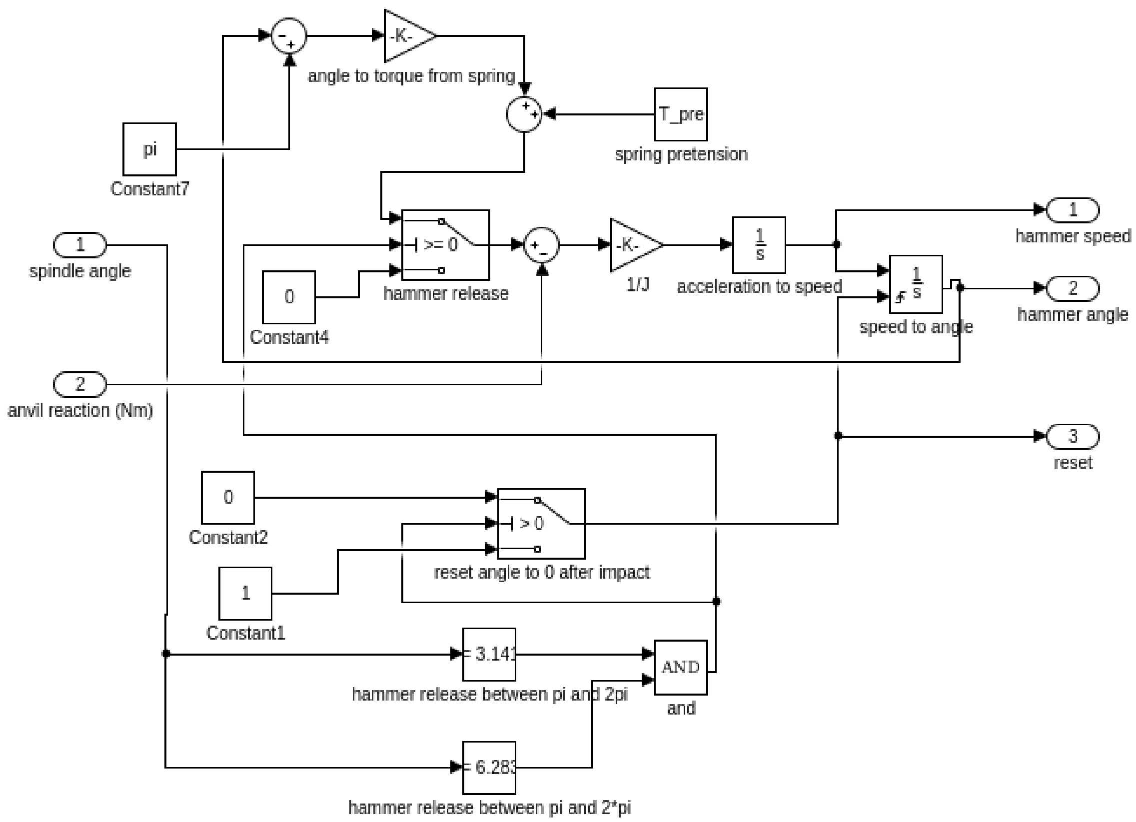


Figure 7.10: Impact drive hammer schematic

7.2.5 Impact drive hammer

Once the spring is fully charged, the steel balls connecting the hammer to the input spindle pass the crest in the v-groove, causing the loaded spring to accelerate the hammer before impacting the anvil. The driving torque depends on the angle according to equation 7.8, where the angle θ is π at the crest of the groove and decreases to zero when the hammer hits the anvil. The acceleration of the hammer is given by equation 7.2, where the load torque from friction in the steel balls is deemed negligible. The simulink model is depicted in Figure (7.10). The switches in the model are needed in order to reset the integrators after the blow is delivered. This is done instead of modeling heat losses in the anvil and bolt, since the main objective of the simulation is establishing the energy consumption, heat development in the motor and achieved torque.

7.2.6 Impact drive anvil

The anvil is thought of as a very stiff torsion spring, modeled with the equation

$$T_a = k_a \theta_a \tag{7.9}$$

, where T_a is the reaction torque in N m, k_a is the spring constant in N m rad^{-1} and θ_a is the angle the spring is twisted with from neutral position. The simulink model of the anvil can be found in Figure (7.11). The switches are used to detect when

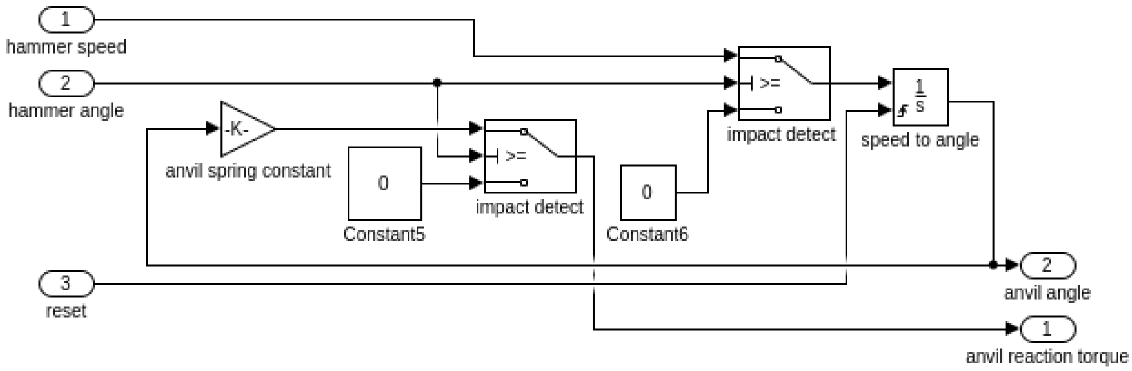


Figure 7.11: Impact drive anvil schematic

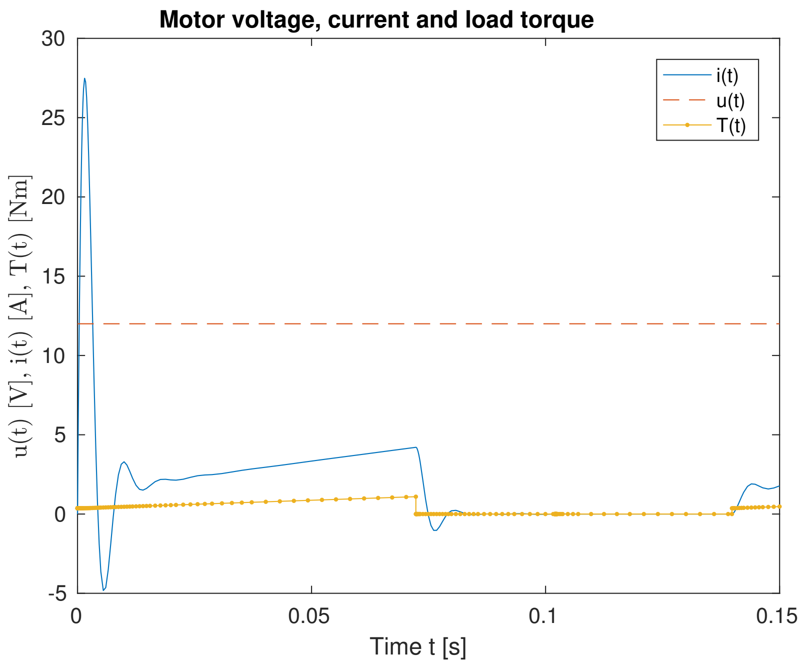


Figure 7.12: Voltage, current and motor load torque during one impact cycle

the hammer reaches π, the angle where the impact happens, and then the reaction torque from the anvil is applied to retard the hammer. The reaction torque, of course, is also the torque that, at most, is applied to the nut or bolt that is being tightened, as the tip of the anvil is considered fixed.

7.2.7 Model verification

Example outputs of the model are detailed in Figure (7.12) and 7.13. The drawn current of the motor behaves as one would expect, and the same goes for the anvil reaction torque. Note that this simulation was made with partially made-up parameters, and simulation results from the real tool will be included in the final report.

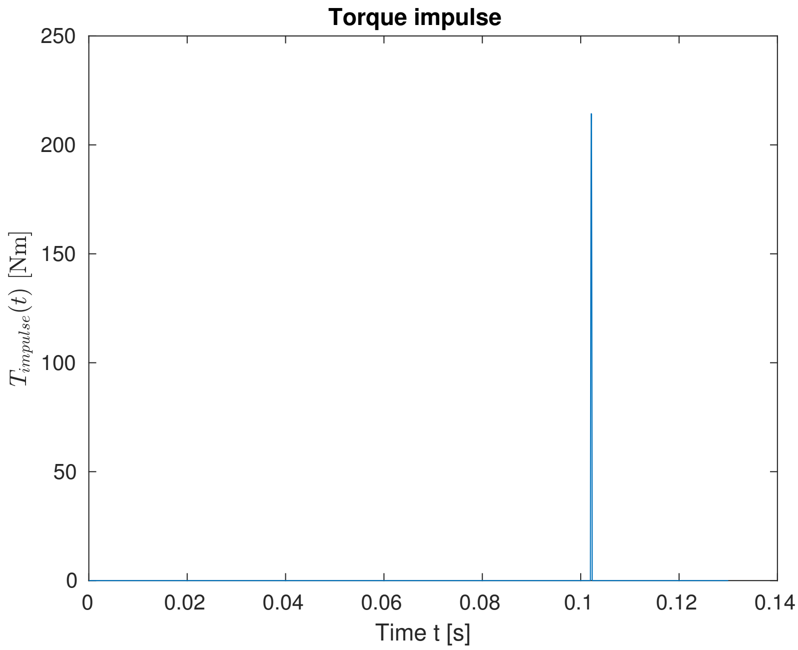


Figure 7.13: Anvil reaction torque during one impact cycle

7.3 Material and Material Selection Process

Since the prototype will be 3D printed, the material of choice for the prototype tool would be Acrylonitrile-Butadiene Styrene (ABS) plastic, although due to the strict budget and limited funding from the Universities, the prototype was printed in Polyactic Acid (PLA) plastics, as this was the only material that would allow the team to stay within the given budget.

PLA and ABS are the most cost effective choices for any prototype that is to be 3D-printed. Both of these materials are thermoplastics, and therefore, they are malleable when heated yet retain their new shape when cooled [23]. Thus, they are both functional for the purpose of assembling the inner components into the tool, and therefore it made sense to print the first round prototype in PLA, as the cost of this material was free through the universities.

After comparing the properties of both materials, ABS has more advantages for building future generations of prototypes, when the budget will allow it. However, PLA was suitable for the scope of this project because the plastic is durable enough to hold the weight of the various components that had to be assembled into it, such as the female RSP connector part, the motor, impact drive assembly, battery, and Raspberry Pi microprocessor, and to also hold together once the tool was turned on. Thus, for the purpose of this first generation prototype, PLA was chosen since it would function as it needed to and because it fit within the budget the best. However, moving forward with future generations of prototypes, it would be beneficial to consider the advantages of ABS if the tool is to be 3D printed and the budget allows it. For example, ABS is more durable than PLA and thus better for the environment in which the tool must perform in. Granted, PLA is more ecologically friendly because it is made from plants and ABS is an oil-based plastic. However, this was one of PLA's only pros over ABS and even though ABS is not biodegradable like its opponent, it is at least recyclable, making it somewhat ecologically friendly. Additionally, ABS is less brittle and has a lower surface hardness than PLA, which is good for the manufacturing operations the tool must perform because these properties imply it is less prone to break when bent [23]. Furthermore, ABS has stronger bonds between its layers, which means it will be better suited to withstand tougher environmental conditions such as chemicals, rough usage, or being dropped. ABS also has a higher temperature resistance which is essential for the mounting and demounting operations, and especially if one wants to use this tool for a long period of time, ABS would be able to endure more heat than PLA which makes it a more beneficial choice. Finally, since ABS has more flexibility than PLA, it allows parts to be interlocked more easily, which is a very important property since the design of the tool head and tool body have parts which must connect [21]. One setback for ABS printing is that a heated print bed must be used when printing the parts, but this is not a big problem overall considering many printers do have heated beds.

Overall, PLA was chosen for the first generation prototype the team built, due to the budgetary constraints of this project. However, for future models that may be 3D-printed, ABS was suggested as the better 3D-print material for these prototypes due to its higher strength and flexibility, which make it more suitable to the environment the tools will be exposed to, as well as its higher temperature resistance, and better machinability properties. Finally, suggestions for mass production of these tools can be found in section 9.

The desires for the material of the final product is that it should be able to cope with fall damages, be oil resistant and functional for mass producing.

7.4 Component and Component Selection Process

This section details the procedure followed in order to determine which components would be best suited for the final product.

7.4.1 Mechanical design

The mechanical design consists of three main components, the tool head, the tool body, and the handles. All of these components have been designed by the team using CAD and then from these drawings they will ultimately be 3D printed. The overall design has been made according to the information given by the sponsor. The following sections describe the reasoning behind the design ideas of these parts, and as mentioned earlier, the interfaces, or ways of connecting the parts together, are detailed in the manufacturing process plan in Table 7.1.

7.4.1.1 Handle

The design of the handle was created based on an individual feel for grip friendliness and before 3D printing, it was evaluated using Human Builder in Catia in order to get proper dimensions. Since grip friendliness and feel is highly individual, a set of handles was designed in order to meet a wide variety of personal preferences. This is due to the fact that operators using the tool have different hand sizes and varying individual preferences. Furthermore, the placement of the button on the handle has a great importance for the human ergonomics, which is why this has been placed based on personal preferences as well.

The idea with the handles is also that a variety of different designs can be offered to the operator in order to get a design that suits that particular operator perfectly. This means that the operator would test the handle by trying it out, just as he or she would try out different pairs of shoes, to see which handle fits the most comfortable in order to maximize effectiveness and safety when using the tool.

7.4.1.2 Tool Body

The tool body is the main part of the tool which holds the Raspberry Pi circuit board, battery, motor, impact assembly, RSP tool changer and it is also the part which the handles and the tool head mount onto.

The limiting size factor of the tool body is the RSP tool changer which is significantly larger size than the other components. Thus, in order to fit the tool changer one of the end parts of the tool body needs to have a diameter of at least 105 mm.

To minimize the used material and to create an aesthetically appealing tool, the tool has a cylindrical shape. It consists of two cylinders, one which has a suitable size for the RSP tool changer and the other (which has a smaller diameter) which has a size suitable for the inner components.

7.4.1.3 Tool Head

In the tool head the impact assembly of the tool will be fitted and so will the camera. Since the tool body has a cylindrical shape, the tool head also has a cylindrical shape to neatly match one another in a joined interface.

7.4.2 Robot mechanical interface

As detailed in section (4.1), the options for the mechanical interface between the robot and the tool was the RSP toolchangers TC-20 and TC-60. TC-60 was chosen for the prototype in order to be able to cope with a counter-torque of 150 N m. This was determined before the decision to use impacting torque was made, otherwise the choice would have been the TC-20.

7.4.3 Drive system

In section 5.5.1 on the drive system, information on electric motors with compatible gears was detailed. These components, according to the product data sheets provided by the vendor, would fulfill the requirements posed by the sponsor concerning speed and torque. The group strove to generate a drive system that would enter the bolt using a continuous torque which initially was required. After thorough research on how such a solution would behave, the conclusion was to not make a solution which would enter the bolts continuously.

The counter torque needed in order to handle such a tool would demand both robust robots as well as strong assembly operators. This is not ideal from an ergonomic point of view and the wear on the robot would be large. Also, the current needed to drive the continuous system with the desired torque would draw a current too large for a compatible controller to handle. A proposal to solve this problem was to construct a gearbox. The highest torque is not needed in an early stage of entering the bolt. Instead demand for torque in the initial stage is low which means that the required current is not high and satisfying controllers were easy to find. But when the bolt enters the final stage, the torque required will be large and at this stage a gearbox with two gears would be suitable. When the tool detects that the torque is too high for the components to handle, feedback would be sent to the overhead system which subsequently would make sure the gear with a larger ratio was engaged. The concept of this solution was only on a basic level but after consultation with experts on mechanical constructions at Chalmers University of Technology, the conclusion was that such a project would be too time consuming to fit in the time frame of this project.

Instead the group considered a drive system which would use the mechanics of an impact wrench that would be able to fulfill the required torque and speed. The impact wrench solution on the other hand would be more difficult to control digitally in terms of torque compared to the original concept. In order to complete a fully functioning prototype, a tool that both a robot and human could handle physically is of greater interest than construct a prototype that works theoretically but not practically.

The components will be taken from a Milwaukee M12 FUEL 3/8" impact wrench [24] which is a medium sized tool that suits the amount of torque and speed the team is striving to attain. Due to Milwaukee's internal data it is difficult to get the detailed information regarding the component's specification. Despite the absence of some data, a rigorous research on the tool was made and the group was convinced that the information that came out of the research was sufficient to purchase the tool previously mentioned. The torque, speed and dimensions seemed to satisfy the requirements and with that as background further tests are to be made on the components.

As mentioned earlier controlling the torque would be more difficult when components from an impact wrench is used. The mechanism of the impact wrench generates high

Table 7.4: Requirements for brushless motor controller

No.	Requirements for brushless motor controller
1	must be able to run drive system motor
2	must be able to deliver 18A current required for impact spring charging
3	must be able to control rotational speed within $\pm 10\%$
4	should be able to measure and communicate current drawn by motor
5	should be easily integrated with the embedded system and motor
6	should allow for short development time
7	should be flexible to use different types of drive system for future prototypes

torque during short periods of time which is beneficial from an ergonomic perspective but not from a digitally controlling point of view. Since the torque is no longer continuous, the intervals in which the torque can be measured is larger because of the impact and will not increase linearly. This results in a decreased preciseness measuring the torque. But as already stated, the customer values a functioning prototype more than one that measures the torque in a precise manner, though the goal, as always, is to achieve both.

In order to control torque, a sensor which could gather information regarding the torque would be compulsory. Instead of using such a sensor, an encoder which could measure the angle on the bolt after it has hit the bottom and return the applied torque is what the team has decided to incorporate in the prototype. The reason behind this is that the angle will be easier to measure instead of directly measuring the torque. From the encoder, feedback is sent to the to the overhead system which will end the process and subsequently stop the motor when the required angle is reached.

7.4.4 Motor controller

Two options regarding the brushless motor controller were available, either using the open-loop controller board from the same tool that the drive system components were taken from, or using a third party controller. The requirements for the controller were derived from the requirements of the tool, as stated in appendix A, as well as requirements posed by other previously selected components are available in table (7.4). Considering the requirements detailed, the third party controllers under consideration were the maxon motors EPOS series controllers[25]. The controller selected was the maxon motor EPOS4 Compact 50/15 CAN, which fulfill all of the requirements stated in table (7.4). The option of using the original open-loop controller only fulfill requirements one and two, and hence it would not enable us to fulfill the requirement on speed control for the tool(requirement three for the motor controller). Considering this, as well as the non-strict requirements fulfilled, the added cost of $500 is reasonable since it is within budget and since the customer values functionality over cost, as long as it is well motivated. The EPOS controllers also have the added benefit that ROS integration is already available in an open-source package utlising the ros_control package and maxon motor provided linux communication library.

7.4.5 Embedded system

The main options for the embedded system, as outlined in section 5.4, were either a raspberry pi zero or an arduino mkrZero. No major new pros or cons were found for each option, resulting in a swift selection of the raspberry pi zero, largely due to its capability to run a full operating system with the full version of ROS (see section 7.5.1) on top. The main disadvantage with the raspberry pi zero is that it by default lacks real-time operating system. According to D. Fontanelli at. al.[26], this is mainly a problem in applications where feedback control is running on the same CPU as other concurrent processes, such as signal processing and communication, where control deadlines can be difficult to meet due to the other processes competing for CPU time. Solutions to this problem include making modifications to the scheduling algorithm in the kernel, as suggested by P. Sousa et. al.[27]. However, this approach is deemed to be outside of the scope for this project, hence the proposed solution is to outsource the feedback control to an external system, as the brushless motor will need peripheral electronics for its operation anyway. This reduces potential timing issues to recognizing discrete states of the tool and updating the reference signal accordingly before deadline. Since these discrete asynchronous events will induce deadlines much less frequently than feedback control, this poses requirements only on soft-realtime. Hence, timing problems will be solved as they arise. Depending on the severity of the timing issue, solutions include swapping the standard linux kernel for ones with varying degrees of realtime scheduling.

7.5 Software

The software structure will feature a modular design, as this is a requirement for the project. Furthermore, communication between the main nodes of the tool as well as with the overhead system is largely conducted via asynchronous events fired on state changes in the tool.

7.5.1 Framework

One of the requirements on the tool from the sponsor is for it to utilize ROS, Robot Operating System. In its base form, ROS is a collection of packages enabling distributed computing. In ROS, computing is done in nodes, standalone units that are executed independently of one another. The nodes communicate with each other using infrastructure provided by the framework. This way, nodes are unaware they are executed on several different machines. This approach also rounds many of the issues arising in multi-threaded programming and promotes modular design of software, which simplifies future development. The nodes can utilize two main types of communication with one another, topics and services. Topics are most easily explained using a twitter analogy; nodes can publish and subscribe to topics they are interested in. The sender is unaware who receives the information, and the receivers do not know where it came from. This way, production and consumption

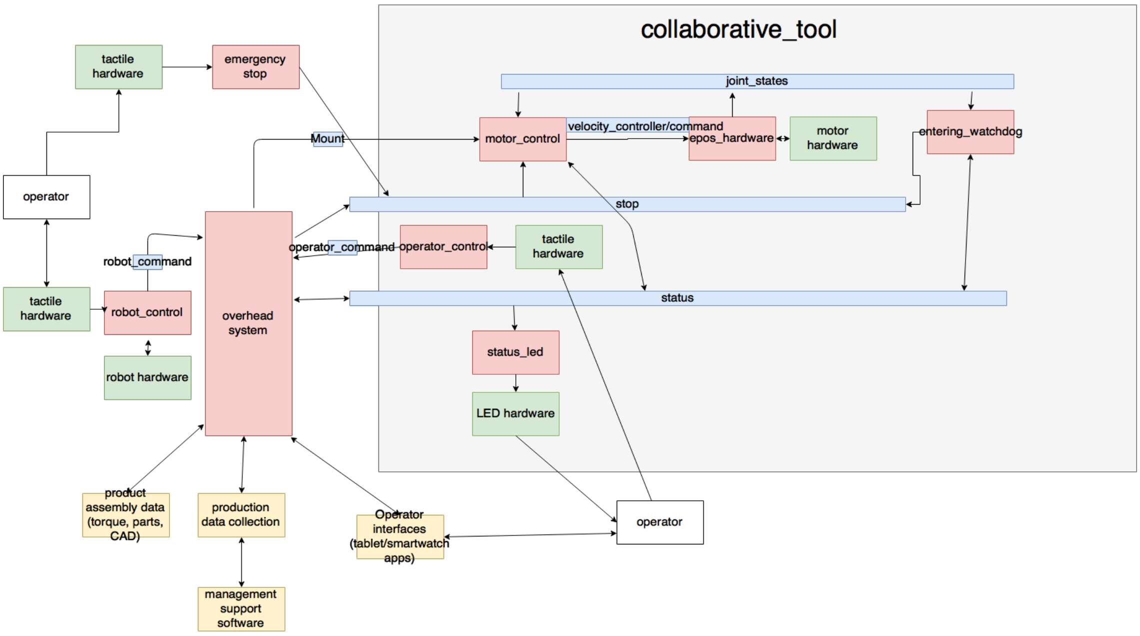


Figure 7.14: Schematic over ROS nodes and topics within and outside the tool.

of information are de-coupled from one another. ROS also provides remapping functionality, which lets the user group and rename nodes dynamically[28]. This feature is of particular importance in this project, since the factory or workshop will want to use multiple tools at multiple workstation, and dynamic remapping means the software can be written as though there was only one tool.

7.5.2 Utilized concepts

Before starting software design, an extensive literature search was conducted in order to come up with concepts from the technological forefront of production system engineering. One such concept is LISA, Line Information System Architecture, which defines a generic protocol for exchanging messages regarding asynchronous events[29]. Whilst the applications stated by Theorin et. al. are out of the scope of this project, the idea of control through anonymous production and consumption of asynchronous events is well suited to the project as a means to reach a modular design as well as to the framework selected (ROS). In addition, Theorin et. al. states the value of having low level data readily accessible for data capture. A goal in the software architecture will hence be to enable data acquisition of both low level raw data as well as asynchronous events derived from that data, which in turn will affect the recognition of which state the tool is in.

7.5.3 Description of main software components

The schematic in figure (7.14) describes how the nodes connect together via topics both inside and outside of the tool. Red boxes represent nodes, blue represent topics and green represents hardware. Orange boxes represent future modules that would be added to the system to complete an entire ROS-based work cell, for example to facilitate data capture and retrieving of assembly instructions.

7.5.3.1 Topics

As described earlier, topics provide the main mode of communication between nodes. The topics used for communication are described in table (7.5).

Table 7.5: Descriprion of topics used for inter-node communication

Topic	**Description**
mount	The mount topic is where the tool receives commands from the overhead system detailing parameters such as the required tightening angle, desired speed, length of the bolt etc.
stop	Emergency stop topic. Used both internally in the tool for stopping when detecting faulty threading of a bolt, and can also be connected to emergency stop functionality in the work cell.
joint_states	Low-level data from the control loop detailing current, voltage, speed etc. Is used internally for monitoring, but can also be used externally if the need arises.
status	The tool uses the status topic to tell its surroundings what state it is in, such as entering, success, failure etc.
velocity_controller/command	Topic for setting the velocity setpoint of the controller.

7.5.3.2 Torque watchdog

The purpose of the torque watchdog is to detect bolts that are entered incorrectly and halting assembly by monitoring torque at different stages in the mounting process. The torque watchdog also contributes to recognizing what state the tool is in by firing events when the bolt has been entered correctly as well as incorrectly.

In theory, the torque required to enter the bolt should increase with the number of revolutions of thread that are entered, since each turn of thread would contribute the same amount of friction. Too large deviations from this linearity would indicate that the bolt has been entered incorrectly, and the mounting process will need to be stopped.

The implementation compares the measured gradient of the torque(current) to a max value set depending on the type of bolt entered, and stops the drive system if the gradient gets too steep.

7.5.3.3 Motor control

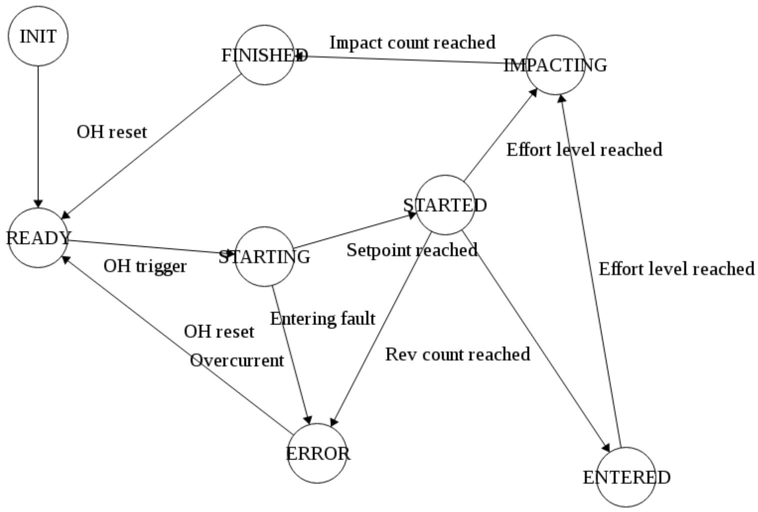


Figure 7.15: Motor control node state machine schematic

The motor control node manages starting and stopping of the tool motor by changing the velocity setpoint value of the lower-level epos_hardware node. The node receives orders from the overhead system on the mount topic, and the overhead system is notified of the status of the order through the status topic, from which the state the tool is in can be read. The node works as a finite state machine, with possible states, transitions and guards depicted in figure (7.15). The node changes state depending on its current state, triggers from other nodes and the measured sensor values (motor torque and speed). Depending on the state the tool is in, the node outputs velocity setpoint values on the velocity_controller/command topic.

The node stops the motor when the number of impacts desired by the overhead system is reached. This is done by measuring the torque output (current) of the motor. Since impacting draws more torque than otherwise. After the impacting current level has been reached, the node starts integrating the motor rotation speed. Since impacting happens twice per revolution when the anvil is at a standstill, the node stops the motor after the number of revolutions required to achieve the desired number of impacts has been reached.

7.6 CAD Renderings

This section contains a rendering of the final tool design which has been 3D printed. The tool consists of the two handles, the tool body, and the tool head. Detailed drawings and more renderings of these parts are attached in Appendix (B). More renderings are attached in Appendix (B). A rendering of the complete assembled tool is found in Figure (7.16).

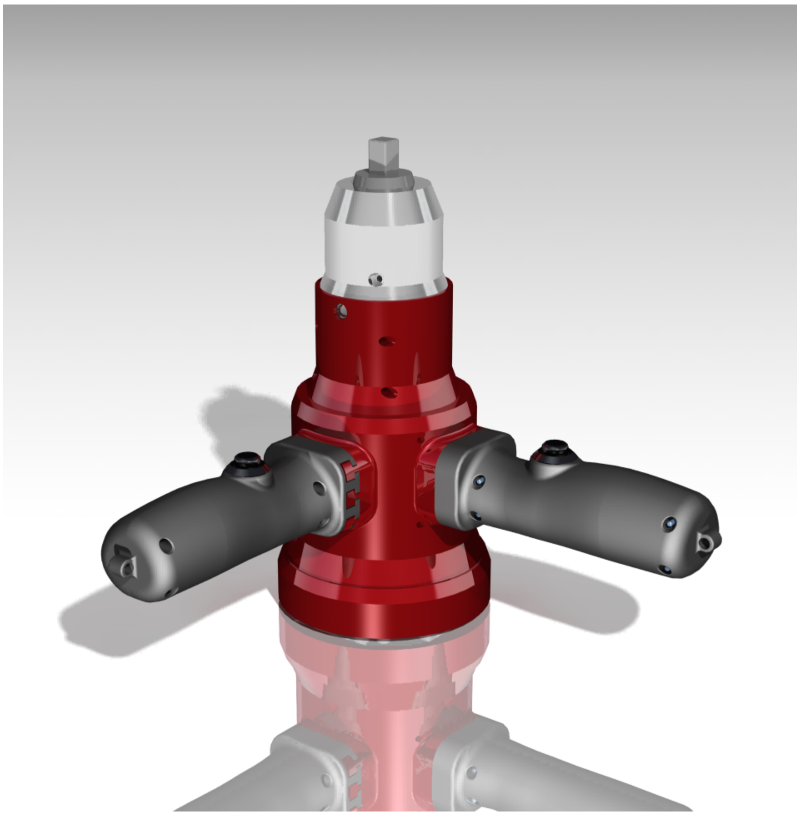


Figure 7.16: Rendering of complete assembled tool

7.7 Test procedure

7.7.1 Reverse engineering and test of drive system components

Since the drive system components were taken from a complete product, data regarding the components were not available, since they are internal information of the vendor. The parameters and data required are listed in table (7.6).

Table 7.6: Drive system parameters usage

Parameter	**Purpose**
Nominal current	Selection of brushless motor controller
Gear ratio	Used in programming to achieve correct speed, battery level simulation
Hall effect sensor connections	Wiring
Stator winding connections	Wiring
Stator winding resistance	Simulation
Stator winding inductance	Simulation
Back-emf constant	Simulation

The nominal current was measured by connecting the Milwaukee tool to two multi-

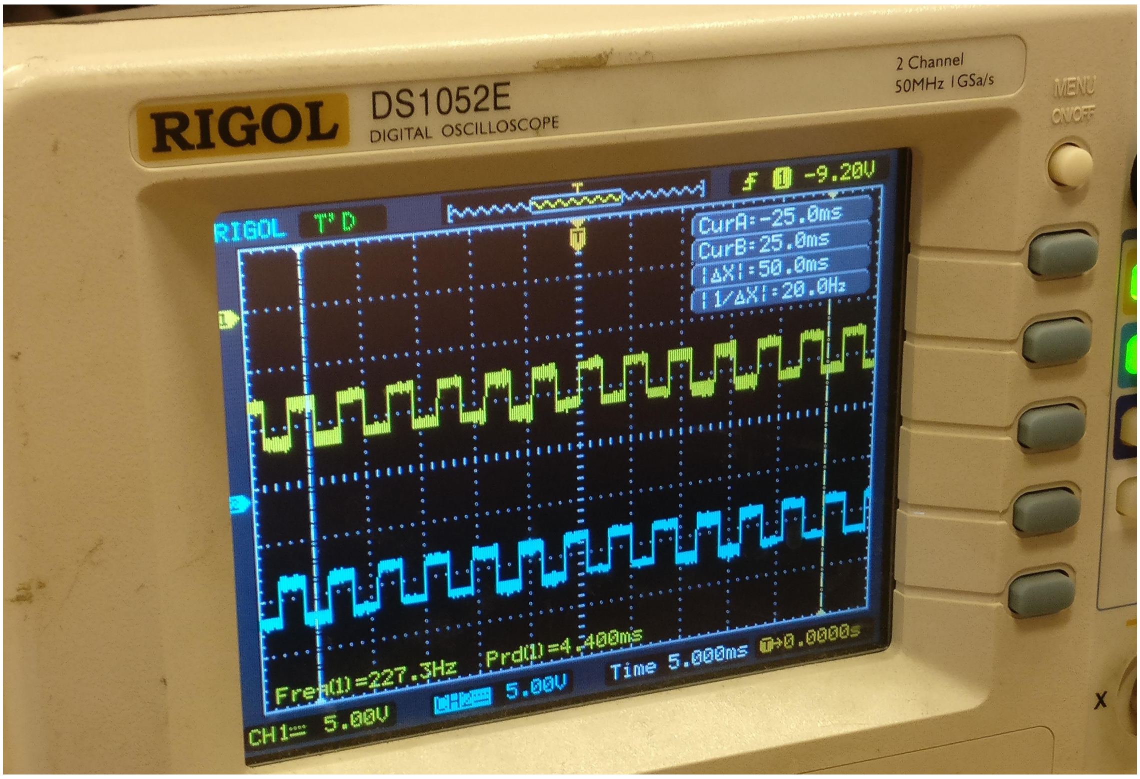


Figure 7.17: Hall sensor waveforms on oscilloscope

meters to measure voltage and current, both with and without load. The gear ratio was measured by hand-turning the impact drive and counting the turns on the input and output shaft. In order to reverse engineer the hall effect sensor connections, the original open-loop controller was connected to a multimeter and oscilloscope in order to determine the position of V+, GND and signals one to three amongst the six sensor wires. The waveforms obtained on the oscilloscope are depicted in figure (7.17). The stator winding connections were reverse engineered using trial and error with the new EPOS controller max current limit set low. The stator resistance and inductance were measured by the EPOS controller.

Once the motor was reverse engineered, it was connected to the new EPOS controller. The controller was initially run through the provided configuration tool, and then switched over to running with the ROS EPOS package and production software on a debian laptop for further testing without the embedded system (raspberry pi).

7.8 Economic analyses - Budget and vendor purchase information

The economic analysis of the project up to this point was put into various tables, which can be found in Appendix C. Since this is a global project, the team is building two identical prototypes, one in Sweden and one in the U.S., in order to enable both halves of the team to perform testing on the component integration. Therefore,

Table C.1 shows the bill of materials of goods purchased in the U.S. and Table C.2 shows the bill of materials of goods purchased in Sweden. Finally, Table D shows the overall total and where the team currently stands with regards to the total budget, as well as the travel funds given by Volvo for each university's respective members to travel to the other university.

The total U.S. budget is $1,000 and with a current projected total of $915, the team is within the given budget. Additionally, the total Sweden budget is 9000 SEK and thus the team is within the given budget there as well. The maxon motor controller was the single largest expense, motivated in section 7.4.4. It is important to note that thanks to the team's universities, the cost of the material for 3D printing the tool parts, the cost of the RSP connectors, and the cost of the wiring for assembly were all free. The overall budget table can be found in Appendix D, and the bill of materials in Appendix C.

8
Final discussion

8.1 Construction process

After 3D printing all the pieces of the tool body, the construction process may begin. First, place the rotor and stator into the tool body that has the opening for wires, as shown in figure 8.1.

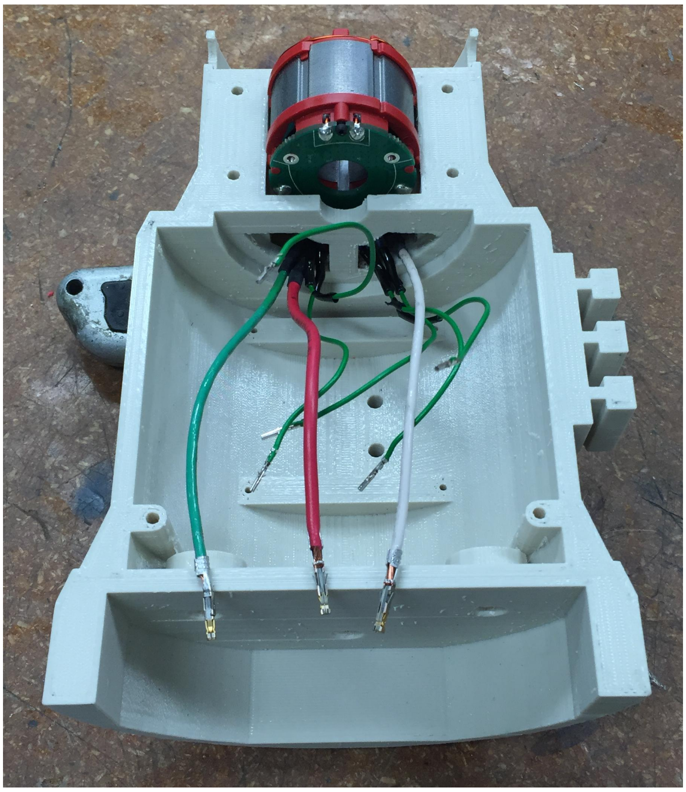


Figure 8.1: Installing stator

The bearing on the end of the rotor was pushed closer to the stator board to fit the tool body and leave room for adding an encoder in the future. Carefully align the stator so the indents fits into the ridges on the tool body. On the side of the stator where the circuit board with connections, you might need to add a small cushion of hot glue or other plastic to align the stator properly, as the stator is supported less because of the hole for cable connections. Figure 8.2 provides a close look to the rotor and stator.

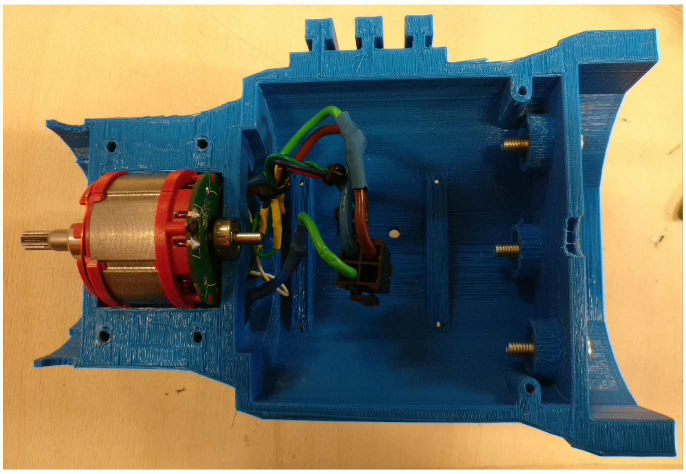


Figure 8.2: Installing rotor

After this is done, use a crimping tool to crimp on all the metal inserts that came with the speed controller, as shown in figure (8.3).

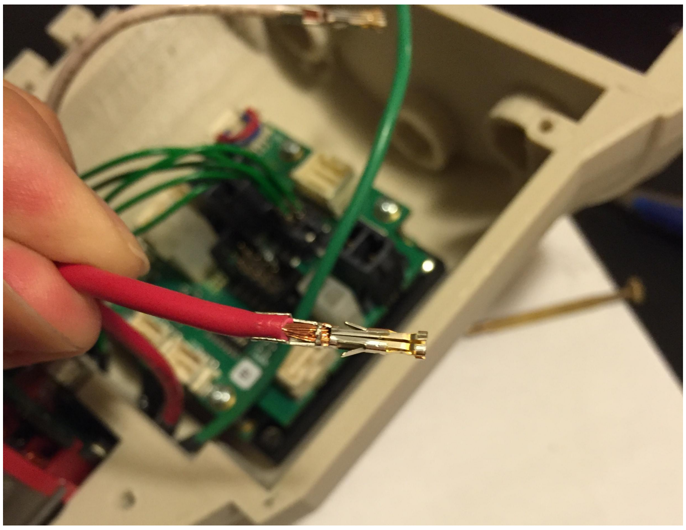


Figure 8.3: Installing metal inserts

At this point the metal inserts can be inserted into the plastic connector housings. The detailed wiring instruction is provided in appendix I. The next step is to install the speed controller, which is bolted on to the tool body by four M3 bolts, and then the contacts may be inserted into the speed controller and the tool would look like figure 8.4.

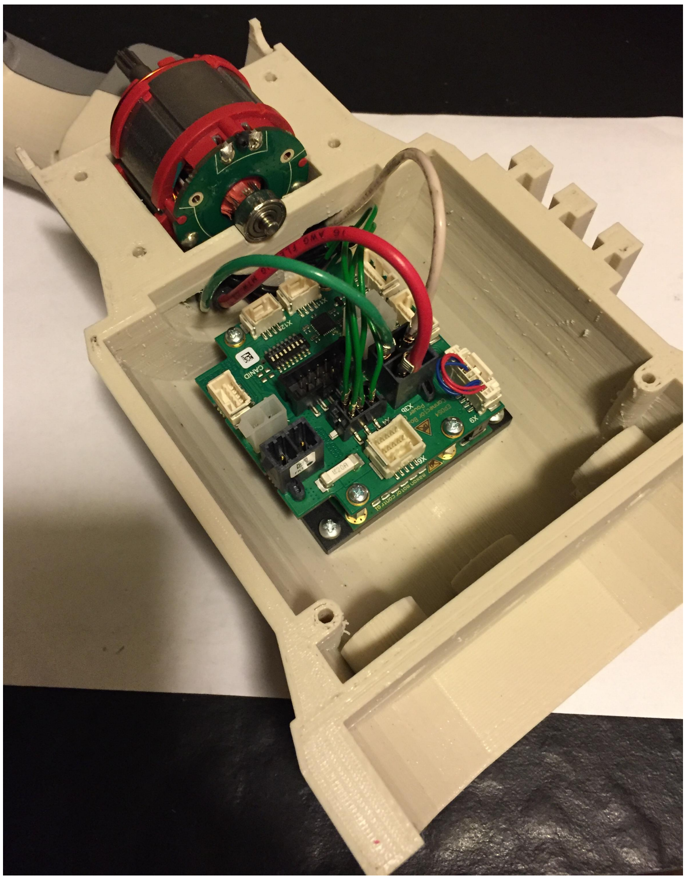


Figure 8.4: Installing speed controller

Then, as shown in figure 8.5, the battery and its output wiring were attached to the other half of the tool body. The RSP connector was also attached to the tool body with bolts and nuts.

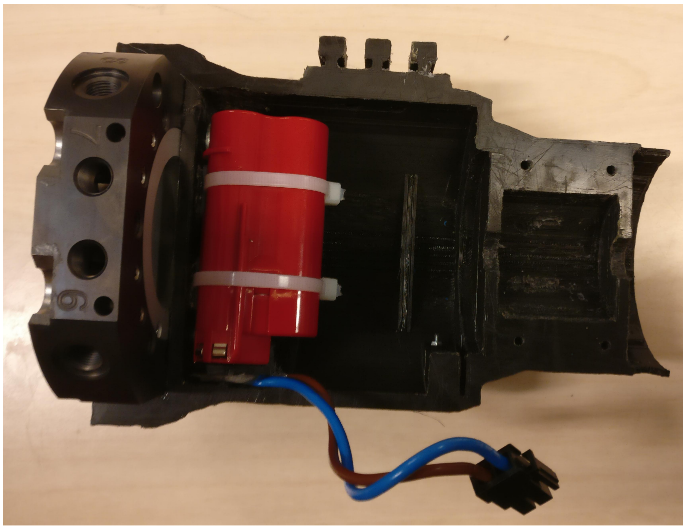


Figure 8.5: Attaching of battery and RSP connector

The construction then move onto the tool head and the handles. First, remove the rubber piece in front of the impact assembly and cut off the extra piece of metal on the back of the assembly as the tool head housing provides the necessary mounting. Then insert the impact assembly into the tool head housing and fasten the two M3 bolts that secures the assembly in place, as shown in figure 8.6:

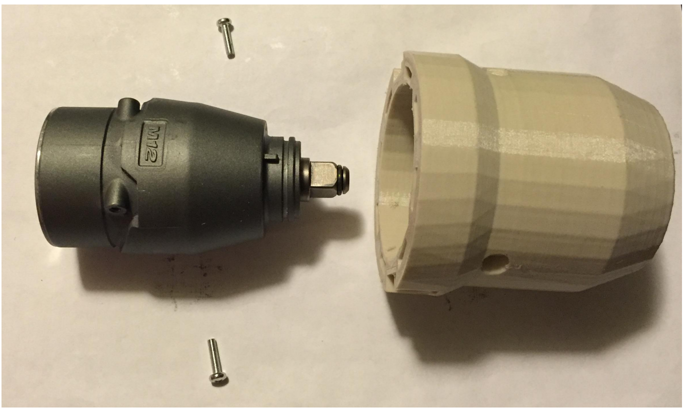


Figure 8.6: Tool head assembly

The construction then moves onto the handle. First place the button into the half handle, hot glue was used to secure it in place. Then connect wires from the back of the button to the metal inserts that's located on the T-slot interface. Then use four bolts to bolt the two halves together. Figure 8.7 shows this process half way through for a better view of the inside of the handle.

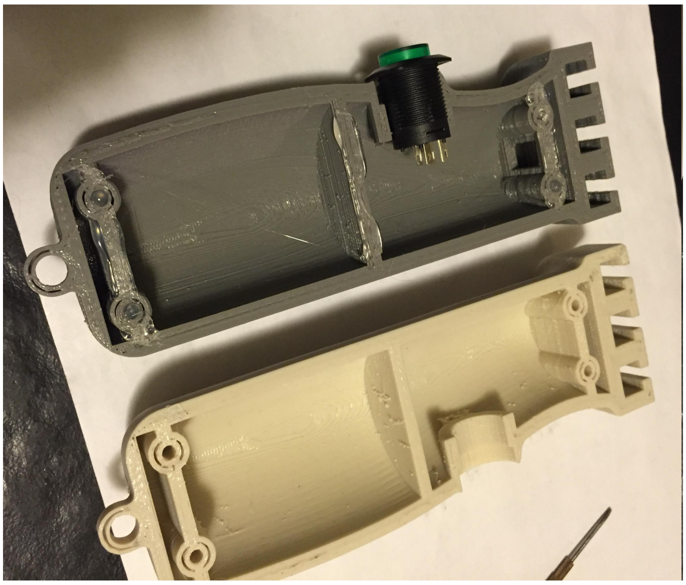


Figure 8.7: Handle assembly

At this point, all the major pieces of the tool is constructed as shown in figure 8.8, Simply slide the handle on and attach the tool head to the main body to the appropriate location.

Figure 8.9: Basic test bench for tool functionality

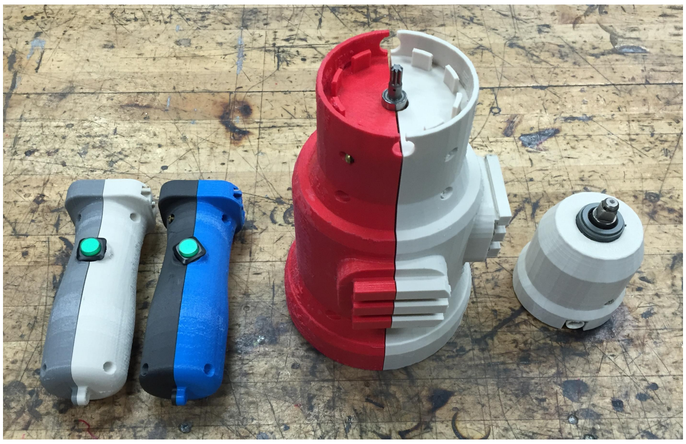


Figure 8.8: Major pieces for the collaborative tool

8.2 Test results and discussion

The tool was tested in a basic test bench as depicted in figure (8.9), where a nut was placed in a vise and a bolt entered and tightened with the tool. During the test, the motor controller was connected to a laptop running debian, since the software was not yet compiled for the target (Raspberry Pi Zero) platform. The functionality of interfaces between components was tested, as well as the motor_control node, which includes the major hardware functionality of the tool, as well as controlling most of the tool state machine, and receiving mount orders from the overhead system.
The test was largely successful, with the different parts of the hardware and software working together as expected. However, fine tuning of the motor_control node is

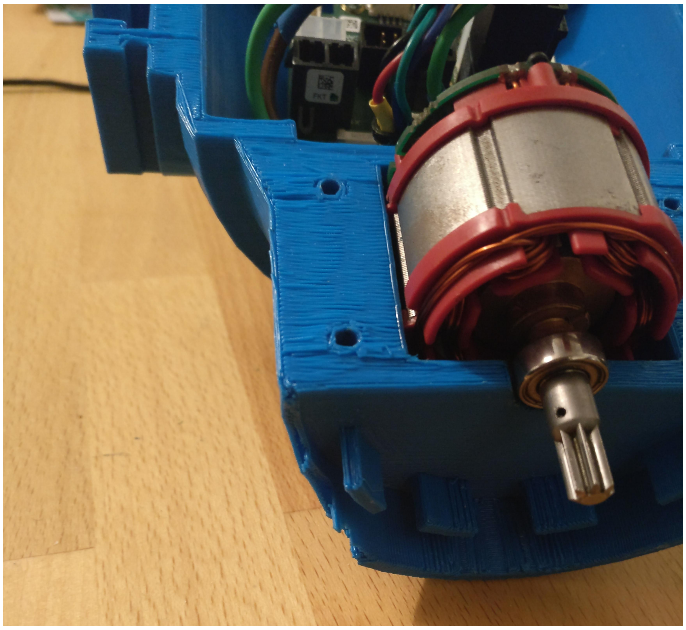


Figure 8.10: Tool drop test result

needed, since the tool did not stop at one impact when set to do so. Instead, the node stopped the motor after three impacts. It is believed that this slight malfunction is due to the node not accounting for the revolutions completed whilst decelerating (the velocity profile, of course, is trapezoid-shaped). However, the target deceleration can be read from the controller beforehand, and hence can be compensated for. This fix has not been tested yet due to time constraints, but will be by the ongoing half of the project at Chalmers.
As mentioned earlier in this section, the motor controller was connected to a laptop for the test and not the target raspberry pi zero. It was believed that moving the software from a laptop running debian to an ARM-based platform also running (a flavor of) debian would be straight-forward, and consequently little time was allocated for this task. As one might guess from the previous two sentences, this was not the case. Since the raspberry pi zero uses an older, armv6-architecture processor, pre-compiled binaries for it are not provided by the ROS buildfarm, and have to be compiled from scratch on the device. For just bare-bones ROS, this is not an issue. However, the epos_hardware package used for communication with the motor controller has wide-spread dependencies that largely have to be resolved manually. This was a time-consuming process, both due to the relatively low speed of the target and inexperience of the operator building the software. When all dependencies had been resolved, it was found that the maxon motor ARM library is compiled for the armv7 architecture, and hence is not compatible with the raspberry pi zero. After having found out from maxon motor that the company no longer provides an armv6 version of the library, the decision was made to switch to a modified raspberry pi 3, whisch uses a newer armv7 processor. The modifications consisted of removing the usb-ports and soldering the controller cable straight to the board, in order to make the larger embedded system fit.

The tool was also drop tested to see if it met with the drop resistance requirement.

The test was conducted from a height of 1.2 meters and for the test to be as thorough as possible, the tool was dropped on the angle where it was deemed most fragile. This resulted in the damage that can be found in figure (8.10). In hindsight, a drop test might be better suited to a later stage prototype than to a first (3D printed) prototype.

9

Conclusions and Recommendations

Overall, the team successfully developed a working 3D-printed prototype that could be used by both humans and robots to perform various mounting and demounting operations. The team achieved this most important customer need by utilizing an impact wrench and speed controller which delivered impulses of torque rather than a continuous torque in order to achieve the needed high speed and torque requirements. The prototype reached a speed of 800 rpm, which was higher than the requested 400 rpm, and it also was able to reach a torque of 160 Nm according to part specifications, which meant it was able to successfully screw and unscrew the M18-sized bolts this project specifically required.
However, the accuracy requirement of $\pm 10\%$ on torque is not met because of to the choice of drive system, which resulted in lack of space where to put neither torque or tightened angle sensors.

From the start of the project the team used the AHP scoring method in order to weigh the given customer needs from the sponsor. After prioritizing the needs, the team hand-sketched four different design concepts and weighed these using the customer needs and various requirements such as safety, ease of use, and portability. Once the ultimate design concept was chosen, it was turned into CAD models and then submitted to be 3D printed using PLA as the material. The final design consisted of one detachable tool head, to allow for various operations depending on the type of tool head attached, one tool body, in which the inner components were assembled, and two tool handles, which attached to the tool via a slide-on interface at a 90 degree angle from each other, in order to give the human user enough control of the tool. The inner components were also chosen with the customer needs in mind, and these consisted of a Raspberry Pi microprocessor, an impact wrench, a speed controller, a rechargeable battery, and an RSP connector. The Raspbery Pi microprocessor works with ROS and thus the overhead system via a WiFi connection and this allows the overhead system to communicate with the tool for various controls such as how many impulses to apply to a bolt, when to move on to the next bolt, and when a bolt has been entered incorrectly. The impact wrench was purchased and then reverse engineered in order to connect with the other inner components so that the tool could be operable by both humans and robots, and so that it could reach the necessary high speed and torque requirements. Once all parts were ordered or 3D printed, they were then assembled into the tool body as outlined in section 8.1, and tests were carried out to measure the speed and impulse torque outputs, as well as the overall functionality of the design, such as that all 3D-printed interfaces aligned correctly. The team successfully met the main customer requirements of utilizing ROS and an RSP connector, being ergonomically designed for both humans and robots, and most importantly, being able to produce the necessary torque to achieve the needed mounting and demounting operations for use in Volvo Trucks' manufacturing processes.

9.1 Considerations for the Method of Manufacturing

One of the biggest future recommendations for this project is how to best manufacture the tool on a mass scale. Currently, the prototype was 3D printed using PLA. As seen in Figure 9.1, the whole prototype took an average of 49 hours to print, which is slow compared to other manufacturing processes.

Part	Print Time 15% Fill Standard Material (hours) (0.2 mm layer height)	Material Used (grams)	Print Time 15% Fill Low Resolution (hours) (0.3 mm layer height)	Material Used (grams)
Toolbody Part 1 (Two Handle Mounts)	20:03	217.21	13:57	204.99
Toolbody Part 2 (One Handle Mount)	17:35	179.35	11:52	167.35
Toolhead	9:13	98.74	6:34	93.51
Handle (Both parts)	11:55	105.83	8:10	97.97
Total:	58:46:00	601.13	40:33:00	563.82

Figure 9.1: 3D Print Times and Weights

It also required work after printing in order to remove all of the added support material which was required during printing due to the complex geometries of the parts. Furthermore, 3D printing can be relatively expensive as well, as even ABS, which is one of the most cost effective options, is usually around $300 to print just one half of the tool body due to its size (when the manufacturing is outsourced and not solely the material cost). Therefore, it is recommended that should the tool enter the mass production scale, the tool should be manufactured using injection molding. When compared to 3D printing in today's market, injection molding has many advantages. First, it is much better suited to handling complex geometries. Instead of building a part layer by layer, the injection mold process utilizes a mold which can handle fine details and very high pressures which enables the production of complex geometries without the need for extra support material that 3D printing must use [30]. It also is a mostly automated process which allows for better tolerances from a CAD drawing that 3D printing cannot reliably produce each time, which again, allows for more complex designs such as those seen in the first prototype. Additionally, one of the biggest issues with 3D printing is the long amounts of time required to print each part. With injection molding however, the times to produce the parts are drastically reduced once the initial mold has been created for each part, which is essential for a company trying to rapidly produce high numbers of parts on the mass scale. Another big advantage of injection molding is that it can enhance the strength of the material through the use of fillers in the molds, and that it can also use multiple plastic types simultaneously.

The current prototype is made of PLA throughout, which is functional but not the most durable of plastics. Thus, one beneficial consideration that could be utilized if injection molding is used to manufacture future tools, is that the tool could be made of lighter materials in certain areas where durability is not of as much concern, such as the handles and parts of the tool body where inner components are not attached, and stronger materials in the areas of the tool body where the inner components must be protected. The use of multiple materials could also be utilized on the handle where a plastic that has more grip capabilities could be molded on the parts of the handle where a worker's hand would go, and the other parts of the handle could still be made of a less dense material in order to ensure the tool is as light as it can be. Finally, the use of injection molding is expected to drastically reduce the cost of manufacturing. 3D printing is currently still a niche market, and thus, the cost of production, especially in more specialized plastics, is still very high compared to other methods of manufacturing [30]. Additionally, since injection molding is primarily an automated process, the overhead and labor costs are reduced which is how this method tends to be much more cost effective than 3D printing when producing large volumes. Thus, overall, the use of injection molding over 3D printing would ensure that the tool could be mass produced in a more time and cost effective way, and the parts would be more accurate with regards to the planned geometries and tolerances when going from CAD drawings to production, which is why it is the recommended choice for future manufacturing of the tool, especially if it is to be done on a mass production scale.

9.2 Future Enhancements

Past the first prototype, there are a few immediate considerations that could improve the functionality of the tool. One consideration would be to use an integrated camera in order to allow the tool to provide guidance when being used by a robot, as a camera would allow the tool to sense and work with its surroundings more, such as being able to determine where bolts are on a table and then moving to the correct spot to pick up a bolt.

Additionally, the goal for the handles of the tool is to be varied from the current design so that each worker can try out different sizes of handles to see which fits best. It would also be possible to create a tracking system of the handles, so that each one is linked to a specific worker via a chip or other identifying sensor, which could then send data to the overhead system in order to be able to track which worker performed which tasks. With todays products being assembled in an increasing number of variants, this identification system could be used when training new assembly operators. In one work cell, a certain operation would be carried out on all products. But on some of them, maybe one in a hundred, the customer has ordered an option requiring an additional operation to be performed in this cell. The overhead system would know when this product enters the work cell, and could then notify the team leader that an operator untrained in this operation is currently stationed in the cell.

The tool body will need to be slightly adjusted to allow for the battery to be charged without having to disassemble the tool body, for example by incorporating wireless charging. Another idea is to make the battery easily replacable, which could be useful when a full charge is needed immediately and simplify servicing. Also, the battery voltage could be increased to, for example, 18 Volts, since the maxon controller allows for a voltage range from 10 to 50 Volts and the supply voltage does not affect the control loop.

Currently, the position encoder that was purchased for use with the motor to provide faster speed feedback to the controller is not used due to lack of space and need for design tweaks in order to make it assemblable. The encoder will improve the control of the motor by providing 512 pulses per revolution complementing the 12 pulses from the hall effect sensors. Then, the hall effect sensors will be used for block commutation and the encoder for the speed control loop.

In the long term, the selection of impacting torque before continuous torque needs to be reevaluated. The selection of impacting torque was correct in this project due to the time constraints on the project, as high torque and speed was deemed more important in a first prototype than precise torque control. If more time and resources are allocated in the future, the idea utilizing a two-speed gearbox as detailed in section (7.4.3) will be worth considering.
One way to measure the angle the rotational design element is tightened with would be to envelop the socket in a color gradient, and then use the camera mentioned earlier to read the color of a fixed spot on the socket. With knowledge of the gradient, the tightened angle could then be calculated.

Finally, in this project, there were no requirements regarding the size of the tool. If the tool were to be used in day-to-day operation, both size and weight would need to decrease. Some suggestions for achieveing this is, firstly, to use a smaller RSP connector, for example the TC-20 instead of the TC-60 used now. The decision to use the TC-60 was made when the drive system was still to use continuous torque. Secondly, the electronics (mainly the embedded system and the motor controller), are currently wired together. The space needed for these components could be decreased by removing the connector board from the motor controller and instead making a custom board connecting it with the embedded system, motor and battery.

10
Self-Assessment

10.1 Customer needs assessment

As this is a first generation prototype for the sponsor, the team felt that the tool deserved a 8 out of 10. The team met the major customer needs of being able to mount and demount rotational design elements, specifically M18 bolts, being able to determine whether a bolt has been entered correctly or not, being ergonomically designed for use by both humans and robots, utilizing ROS and an RSP connector, having a WiFi connection to communicate with Raspberry Pi, and of achieving the necessary amount of torque needed to perform the operations. However, at this point, the team did not include more complex sensing capabilities such as a camera which could give the robot more efficiency by allowing it to be able to have more of a connection to its surroundings, mainly due to time constraints. This function can be easily implemented however, as the design of the team's tool was created with being able to fit a camera in the tool head in mind. Furthermore, the team did succeed in having a cordless power supply, as the tool uses a rechargeable battery, although the battery is currently assembled into the tool body which is assembled via screws. Thus, with the way the current prototype is designed, the tool is not as portable as desired since the tool body will have to be disassembled to charge the battery when the battery dies. Additionally, the selection of drive system components from a finished product resulted in lack of space for sensors to measure actual torque output or tightened angle (which was also accepted by the customer). This resulted in a solution where the number of impacts delivered can be controlled, but not the result of the impacts. Hence, it cannot be known whether the delivered torque is within $\pm 10\%$ of the setting, which was a customer requirement. Due to these three reasons, the team deducted two points off of the score, resulting in an 8 out of 10. Though the score is not perfect, the team believes that the prototype is successful in meeting the most important customer needs and that it serves as a platform for future generations of a collaborative robot tool for mounting and demounting various rotational design elements.

10.2 Global and societal needs assessment

The team deemed that this first generation prototype deserved a 9 out of 10 in meeting the global and societal needs. The prototype successfully met the societal need for a tool which could help with truck manufacturing operations in the expanding collaborative robot market. The tool was also designed to be easily operable by both humans and robots. Specifically, a second handle was added to the intitial design in order to give the human operator more control over the tool while it is in use. This feature helps to ensure that the tool is safe to use by humans, and since it also features wireless connections, and the necessary connections to the robot arm via ROS and the RSP connector, the tool is also safe to use by robots. Finally, it is free of hazards such as cords or wires hanging from it which means it is very safe to move around in a factory setting and will not cause any fire or tripping safety issues. Therefore, the tool successfully met the safety needs. Additionally, though the nature of this project was not the type in which it would drastically improve or harm the environment, the team did consider environmental considerations when possible. For example, the material of the 3D printed prototype, PLA is extremely environmentally friendly, as it is made from plants and is biodegradable. Furthermore, the recommended plastic for future 3D-printed prototypes, ABS, is somewhat ecologically friendly as well because it can be recycled. Another environmentally friendly component is the use of a rechargeable battery as the power source, because this means the same battery can be used for years, which reduces the amount of harm to the environment since the tool will not require large amounts of electricity or the use of new batteries every week had the team used un-rechargeable batteries. However, these kinds of batteries are not currently fully recyclable so from a sustainability standpoint, a more ecofriendly power source could be integrated should it function correctly for the necessary operations required of the tool. Finally, the tool was designed to help improve the efficiency of truck manufacturing processes, and since the prototype can be used efficiently by both humans and robots interchangeably, the basic human need for a more effective manufacturing process was successfully met. Therefore, the team felt that besides the power source not being completely recyclable, the final prototype met all other global and societal needs which is why the score was a 9 out of 10.

One important aspect to have in mind is how the robots today are taking over in many different fields. One this tool's purposes is to facilitate the assembly operator's work. For example, when the bolt is properly entered feedback is sent to the operator who subsequently can move on to the next operation. Human errors will therefore be eradicated to a greater extent and as a result of that the product will be more reliable. The same conclusion applies when the tool is mounted on the robotic arm which in this case will not involve a human operator at all. Although the advantages are many, the role which humans play in assembly decreases when robots and intelligent tools are taking over. The assembly operator will no longer have to assess whether the bolt has been entered correctly or not and when the robot is substituting the person who previously did the robots job, it will inevitably make the human assembly operator superfluous which will result in increasing unemployment rate. According to Moshe Verdi, [31] professor at Rice University, the unemployment could be as high as 50 percent within a few decades. This is not only of concern for the truck production companies such as Volvo Trucks but for most fields where robots can perform a human task.

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A
Engineering specifications

The tool must

- weigh less than 3.6 kilograms
- be able to mount and demount rotional design elements
- be able to deliver a torque of at least 70 Nm
- be able to enter-screw-tight, 80mm M20 screws at 80Nm in $<$ 5 seconds
- be able to mount 8 M18 bolts, 10 second in between, 50 times per 8h, evenly spread over the day
- have a cordless power supply
- be able to distinguish between correctly entered screw and incorrectly entered screw.
- use ROS as software platform
- communicate with its surroundings wirelessly with other units running ROS, including the torque to which a screw should be/has been tightened
- be able to control fastening torque and speed within +/- 10%
- be operated with one or two hands by humans
- be able to determine for itself if it is being operated by a human or a robot
- use an RSP tool changer as interface to the robot
- be resistant to oil
- be able to operate in a temperature span of 5-40 degrees celcius
- comply with the Swedish work authority's regulations regarding industrial assembly
  - have a noise level of less than 55dB
  - not convey vibrations larger than 5 m/s^2
- be able to withstand being dropped from 1.5 meters

The tool should

- be able to deliver a torque of 100Nm clockwise and 150Nm counter-clockwise
- weigh as little as possible
- be as ergonomic as possible
- be as quiet as possible
- be able to communicate if a screw has been entered correctly to a operator
- have a modular design with one main part and ability to connect different tool heads
- tool heads should be easily interchangeable
- be able to perceive its surrounding mainly to communicate positiong data to overhead system
- be able to do processing of sensor data onboard

- have a service life of at least 3000 hours
- be easy to service, regarding battery replacement and lubrication

B

CAD-Drawings

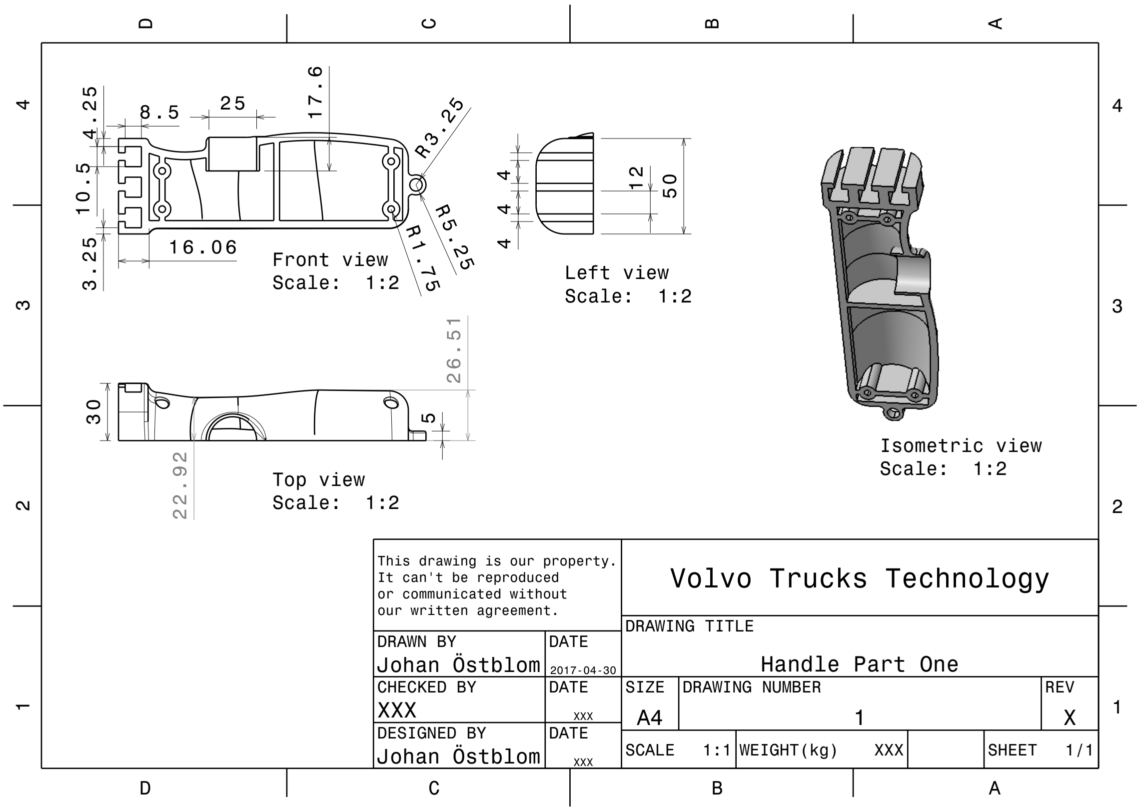


Figure B.1: Detailed drawing of one half of the tool handle

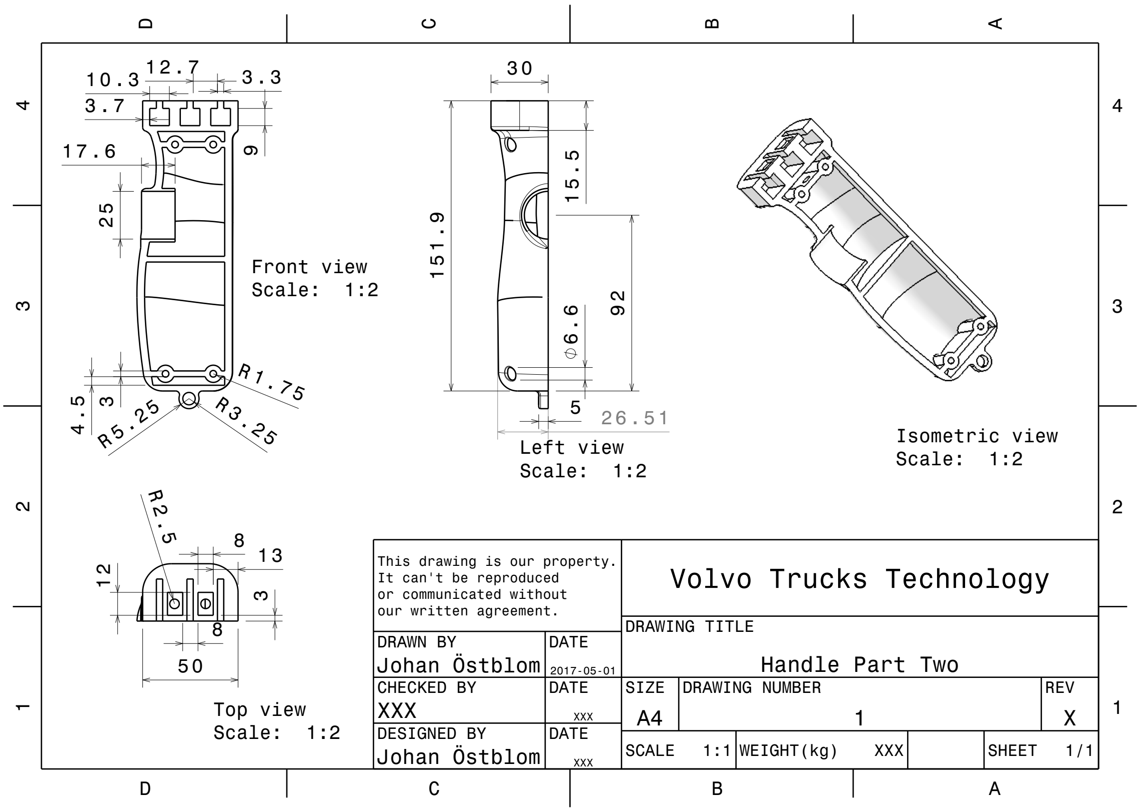


Figure B.2: Detailed drawing of the second half of the tool handle

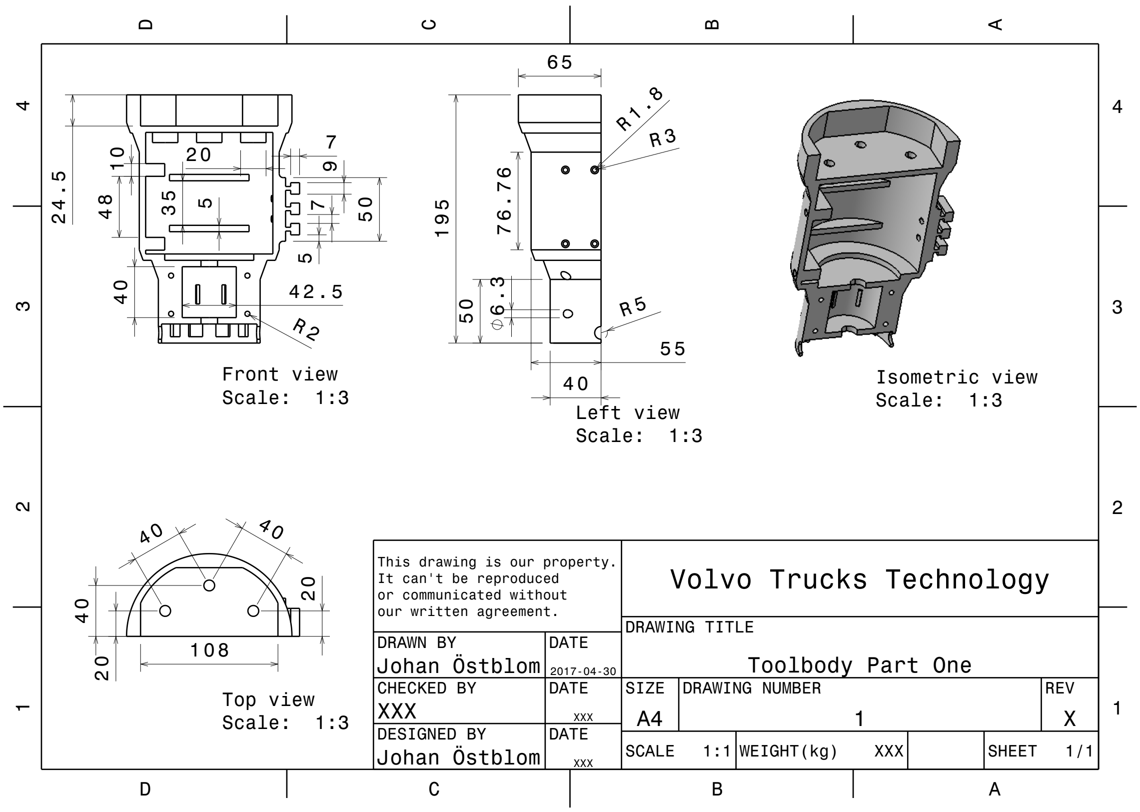


Figure B.3: Detailed drawing of the first part of the toolbody

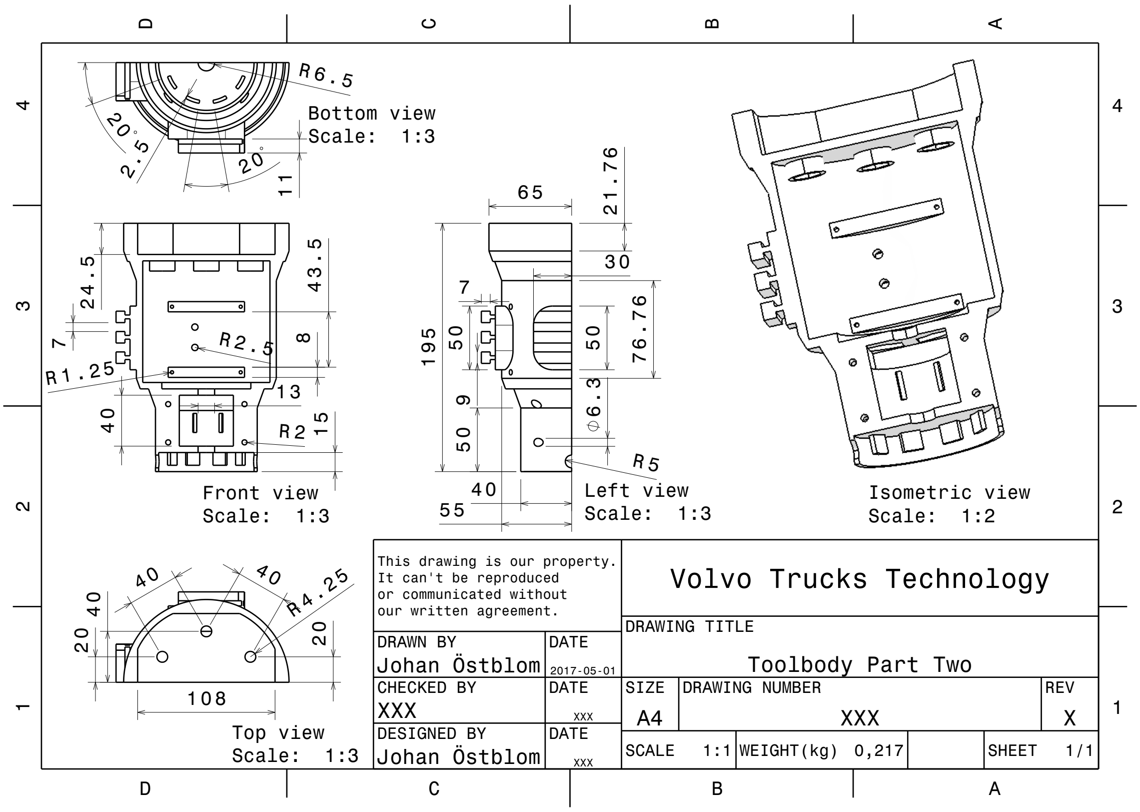


Figure B.4: Detailed drawing of the second part of the toolbody

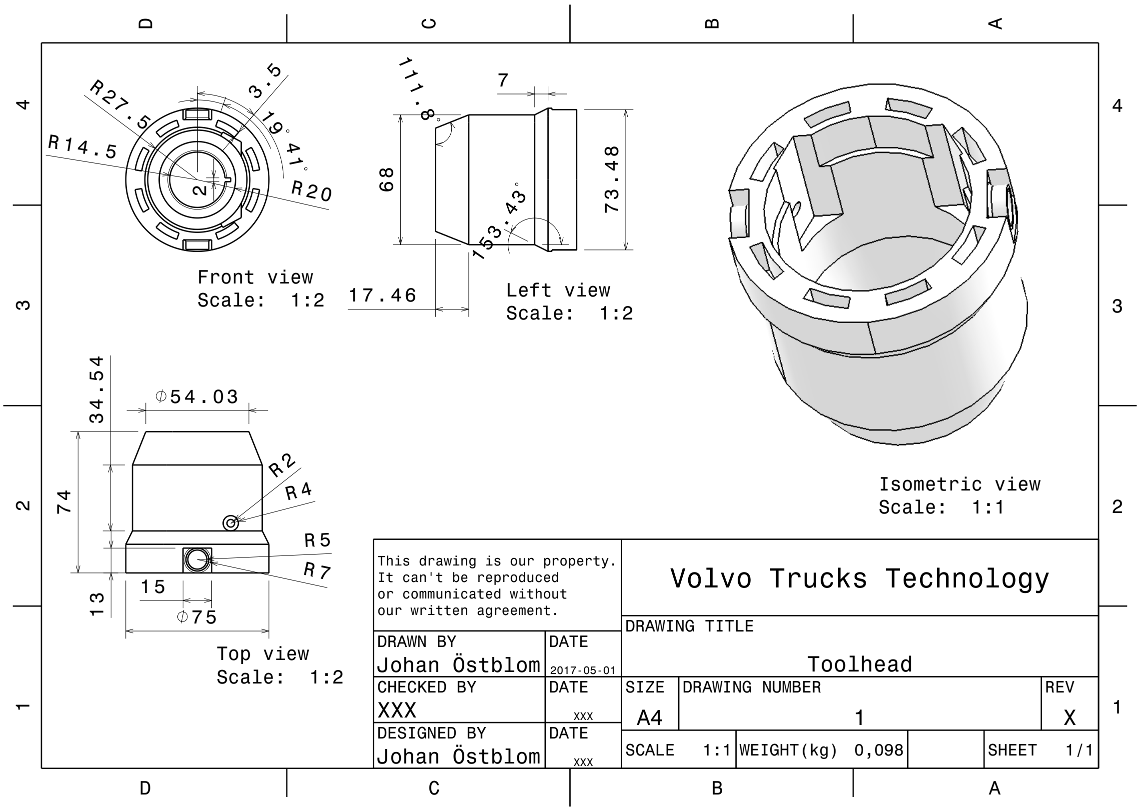


Figure B.5: Detailed drawing of the toolhead

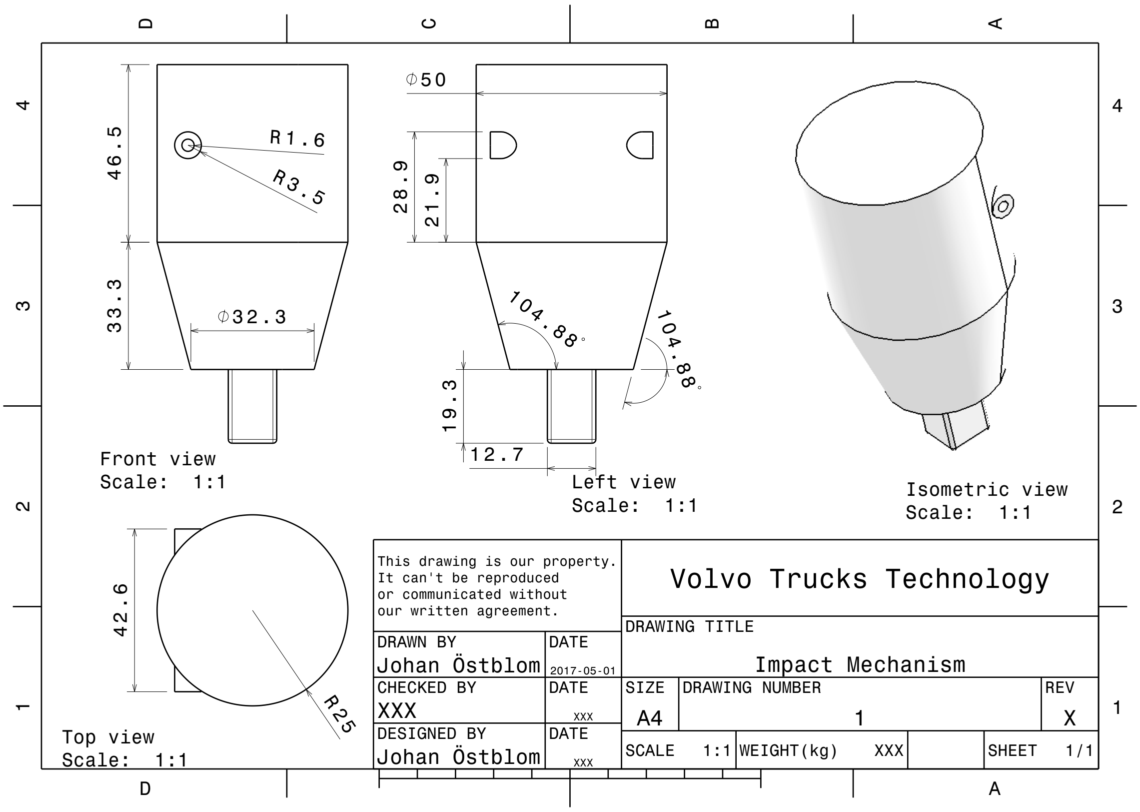


Figure B.6: Detailed drawing of the impact mechanism

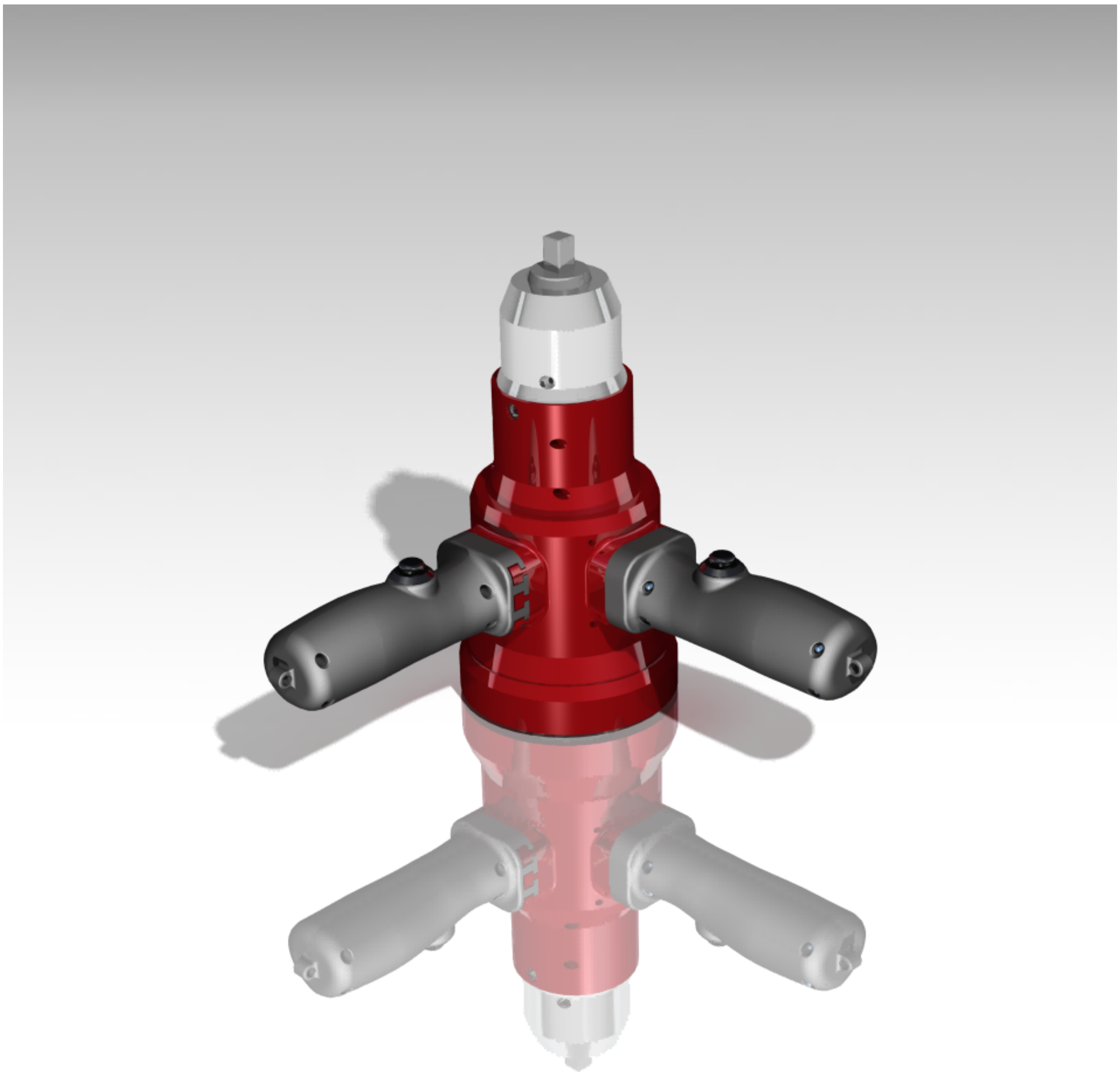


Figure B.7: Rendering of the final tool

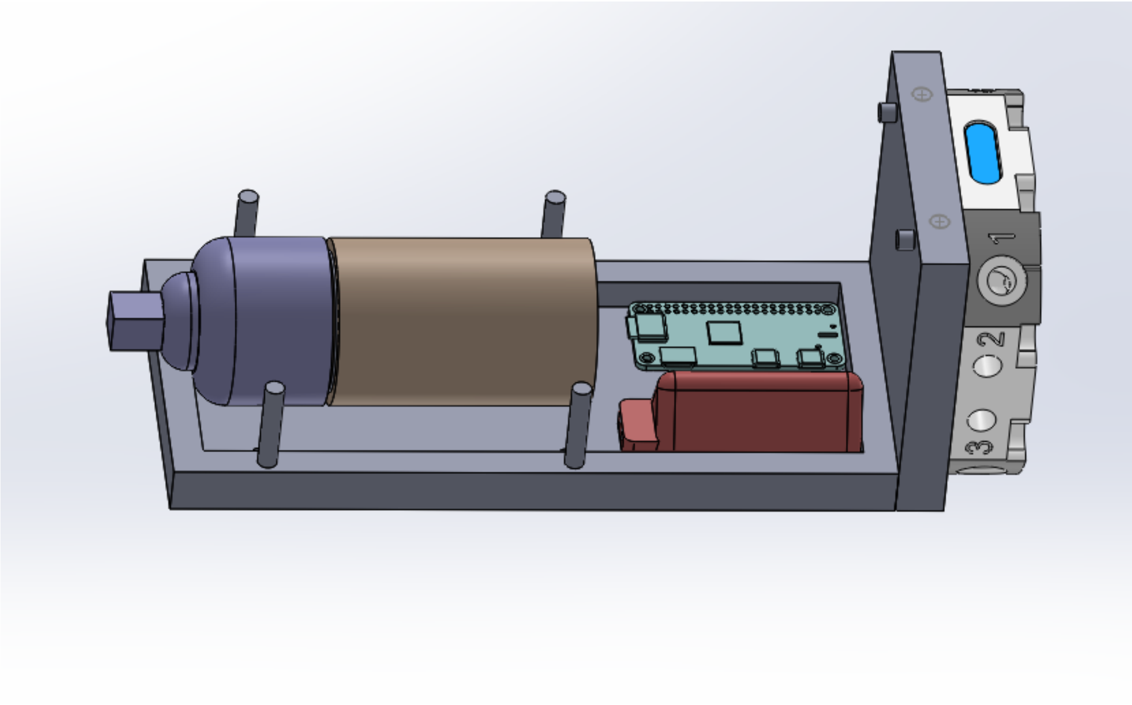


Figure B.8: Rendering of 3D concept 2 (which was not selected) for the tool body with inner components showing

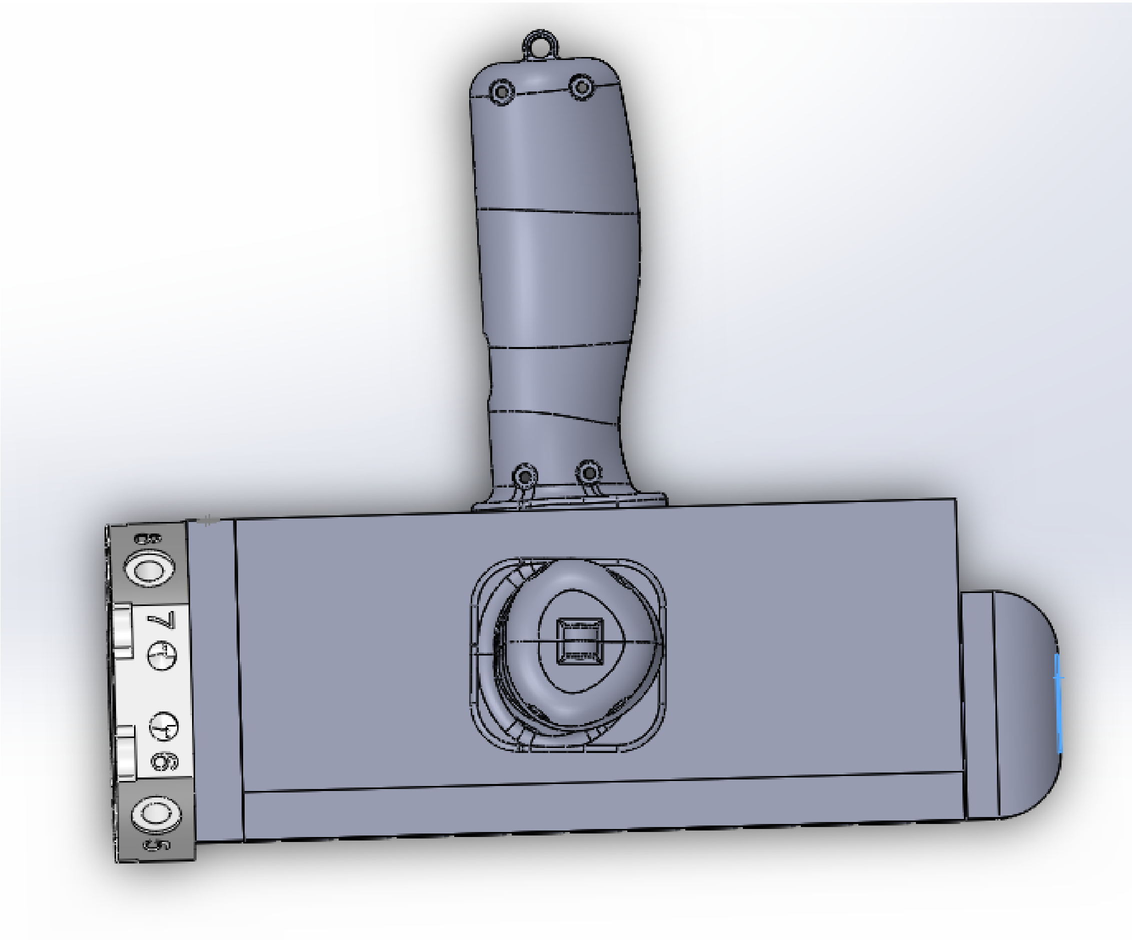


Figure B.9: Rendering of 3D concept 2 (which was not selected) for the tool body with top and handles shown

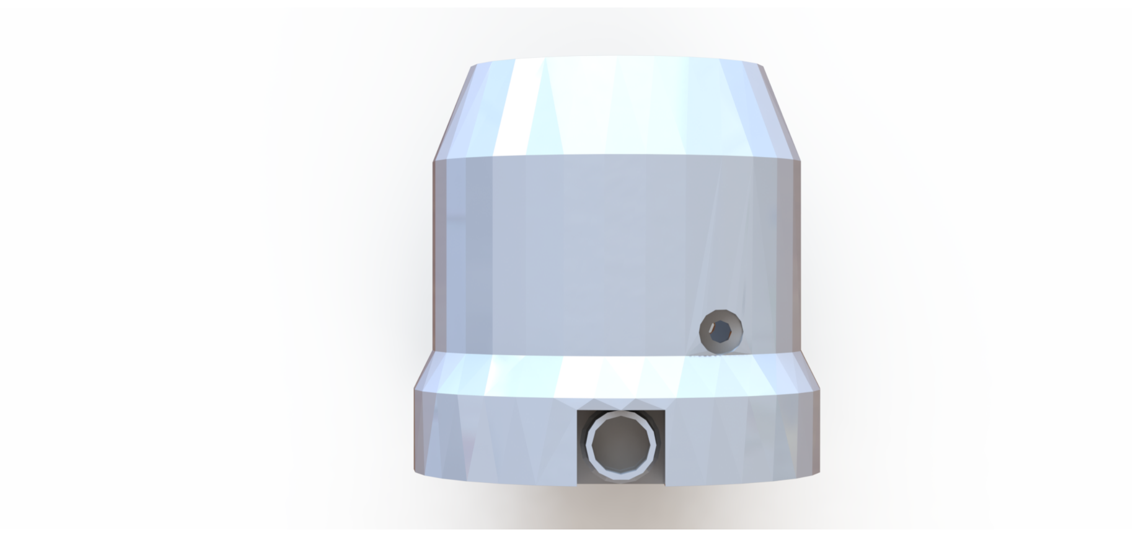


Figure B.10: Side view rendering of 3D concept 1 for the tool head, which features holes for spring loaded buttons and a camera

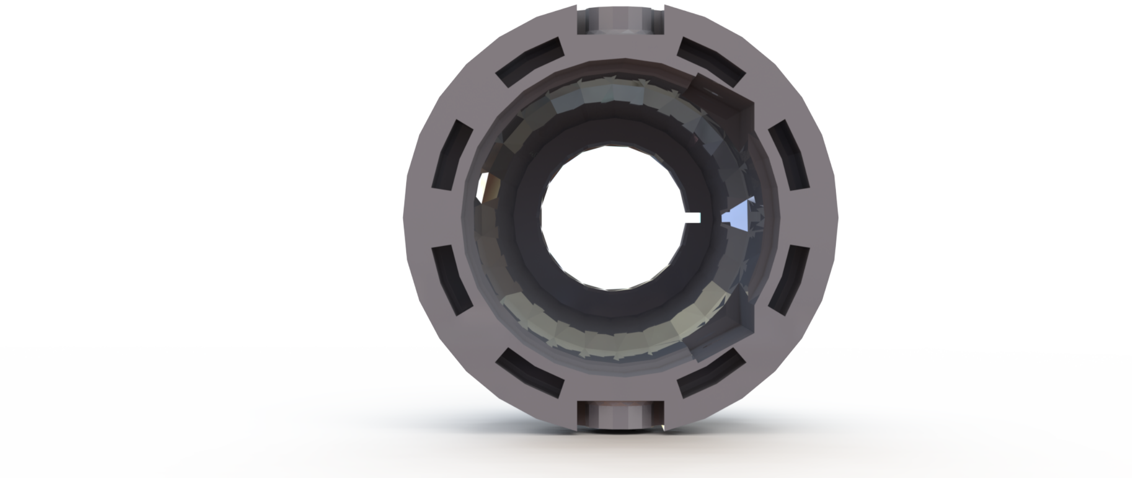


Figure B.11: Bottom view rendering of 3D concept 1 for the tool head, which features a snap on-designed geometry which fits onto the respective geometry on the tool body

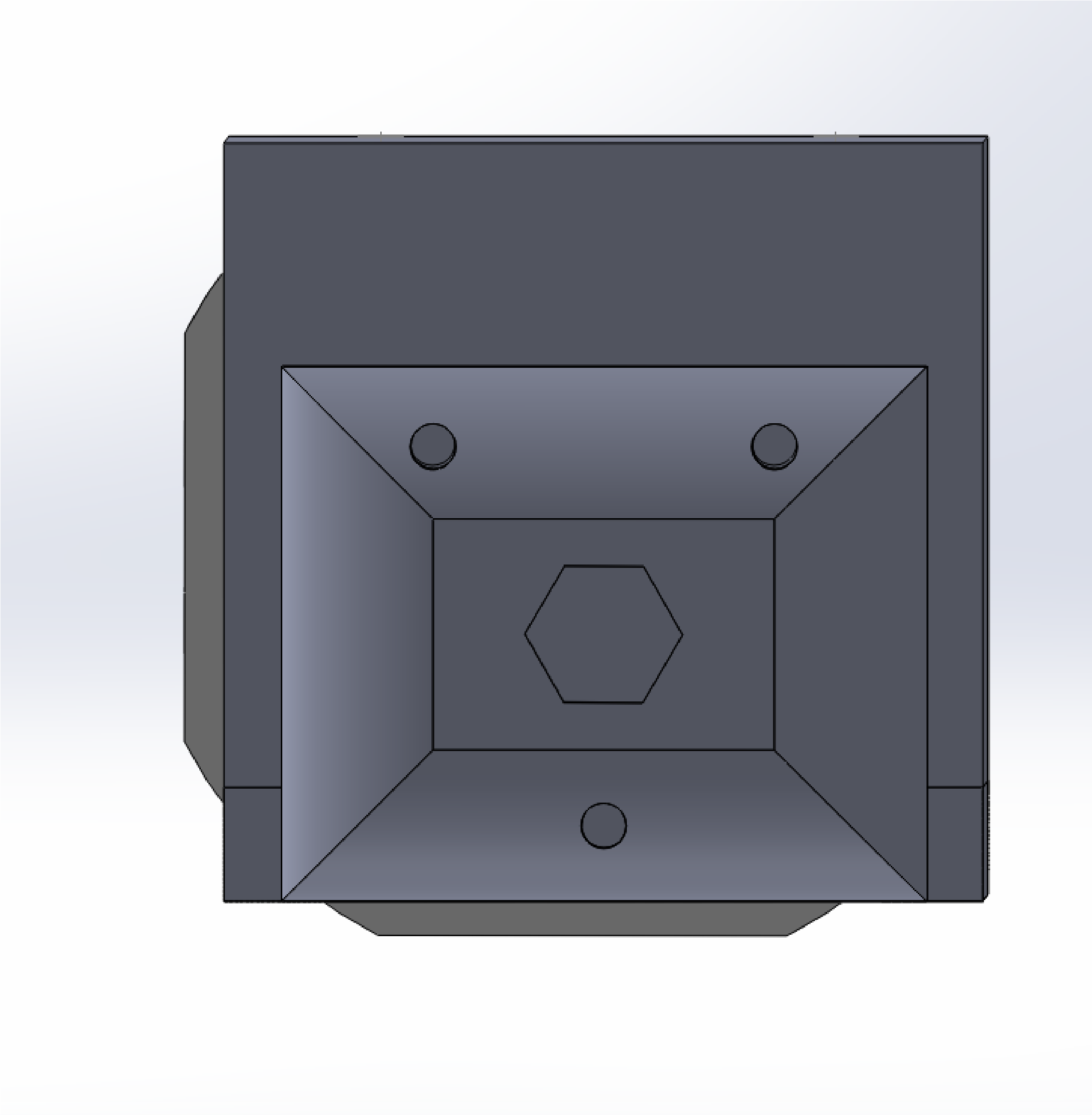


Figure B.12: Rendering of 3D concept 2 (which was not selected) for the tool body with focus on the tool head connection

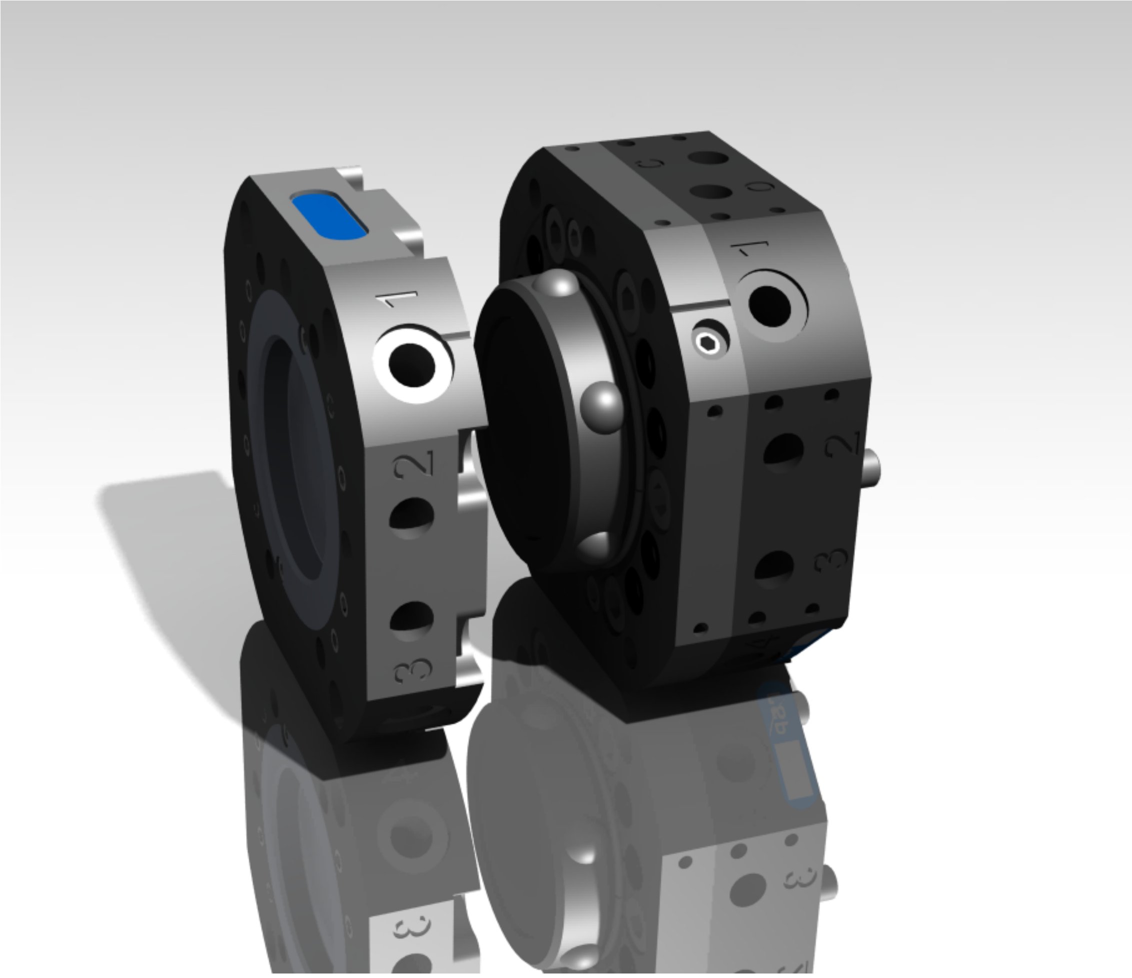


Figure B.13: Isometric view of RSP tool changer, show how the two parts interlock with each other

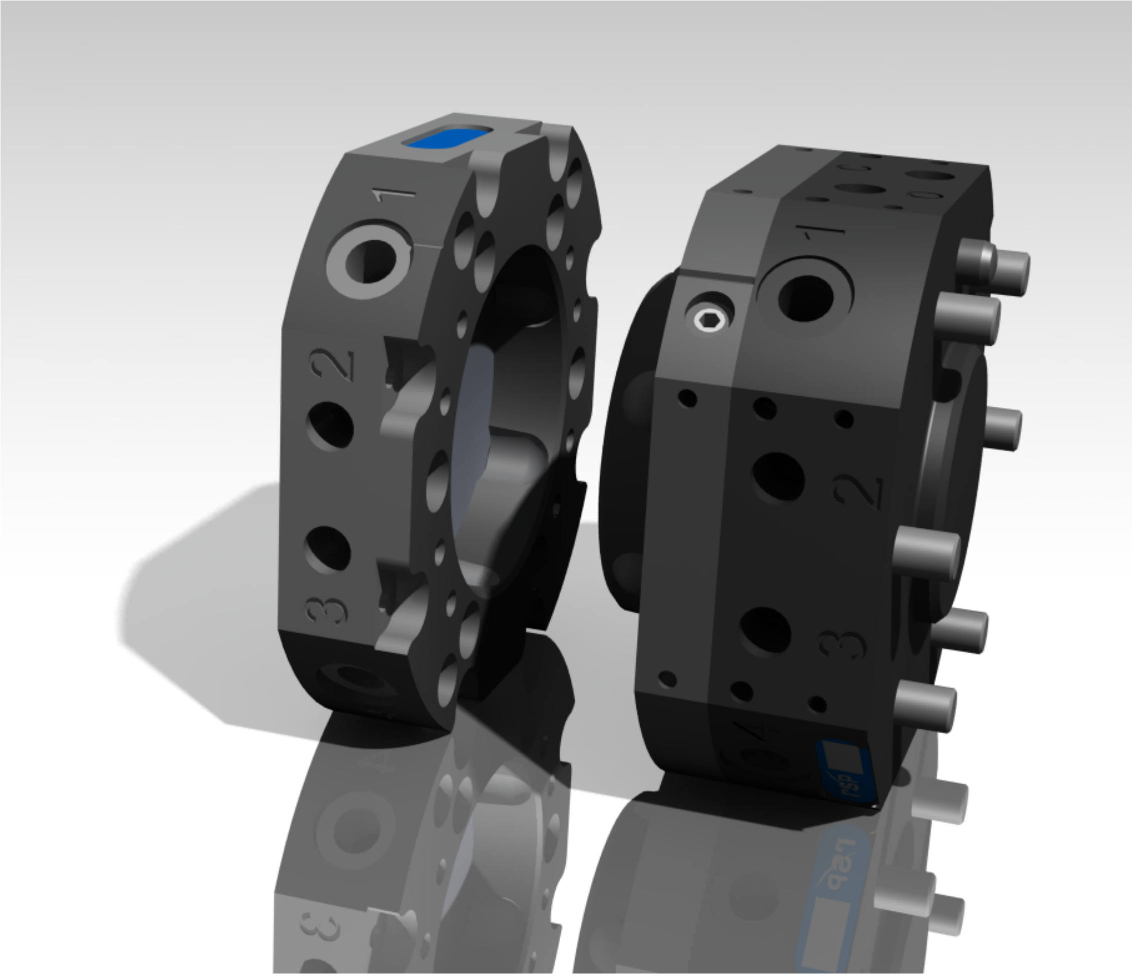


Figure B.14: Sideview of the RSP tool changer

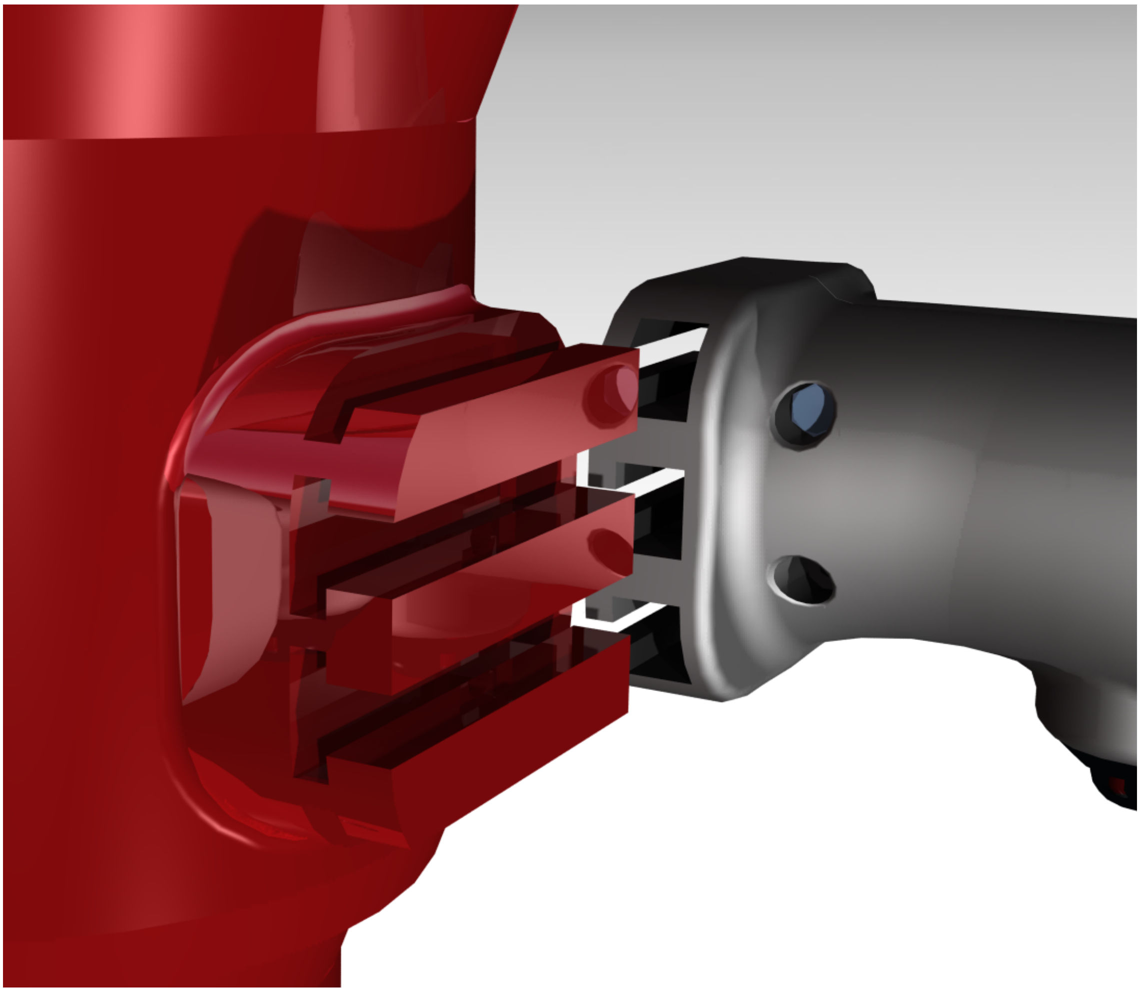


Figure B.15: Interface between the tool body and the handle for chosen 3D concept 1.

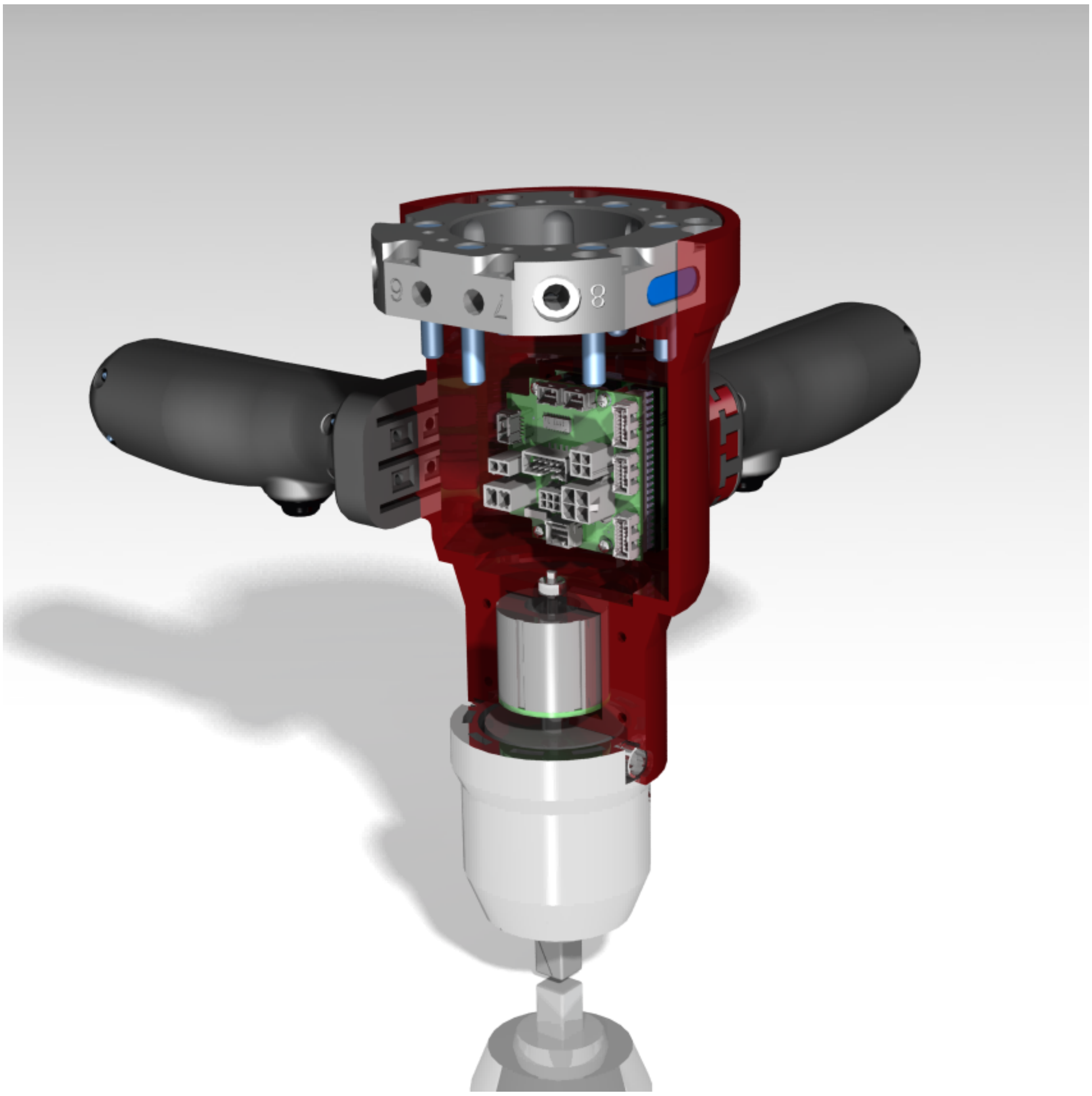


Figure B.16: Cross section of the tool

C

Bill of materials

C.1 U.S. Bill of materials

Material	Quantity	Total Cost
Raspberry Pi Zero W	1	$23.00
Gyroscope	1	$10.00
Milwaukee 2454-20 M12 Fuel 3/8 Impact Wrench tool	1	$148.52
Milwaukee 48-59-2401 M12 Battery Charger	1	$26.80
Powerextra 2 Pack 12V 2500mAh Lithium-ion Replacement Battery for Milwaukee M12 Milwaukee 48-11-2411 REDLITHIUM 12-Volt Cordless Milwaukee Tools Milwaukee 12V Lithium-ion Battery	1	$32.99
Maxon Motor Controller	1	$470.00
Push Button	2	$12.90
Poster for Showcase	1	$62.24
Screw Replacement	1	$5.00

C.2 Sweden Bill of Materials

Material	Quantity	Total Cost
Raspberry Pi Zero W	1	150 SEK
Milwaukee M12CIW M12CIW12-202C 12V 2X2, 0AH FUEL 3/8	1	3051.40 SEK
Maxon Motor Controller	1	5800 SEK
Push Button	2	60 SEK

D
Budget table

	Travel	Given Budget	Total Amount Spent (excluding travel)
U.S. Budget	\$4,200.00	\$1000.00	\$915.65
Sweden Budget	\$4,200.00	SEK 9000	SEK 8591.67
Team Total	\$8,400.00	\$1569.43	\$1886.20

E

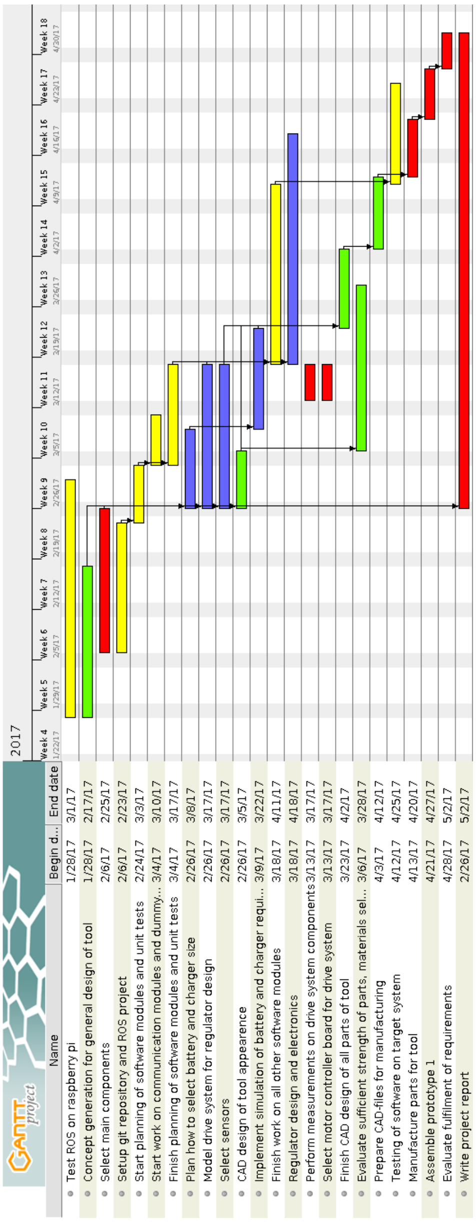
Existing patents

PatentName	**Patent Number**	**Status**
Automated tool change assembly for robotic arm	US 20120207538 A1	Active
Robust manual connector for robotic arm end effector	US 8992113 B2	Active
Isolated Force/Torque Sensor Assembly For Force Controlled Robot	US 20160202134 A1	Active
Robotic tool changer	US 8005570 B2	Active
Breakaway tool coupler for robot arm	US 5954446 A	Expired
Robotic arm tool head selection and storage rack	US 5372567 A	Expired

F

Gantt chart

Figure F.1: The chart is color coded, with yellow for software/embedded, blue for drive system, green for design/mechanical and red for group common



G

Table of risks

Category	Risk	Level	Action to Minimize
Project Mangament risks	Problem with communication due to the vast distance between the two parts of the team	High	Double check if something is unclear and answer messages as quickly as possible.
	The time it will take to finish a subtask might take longer than expected	High	Set up a deadline for the subtask and inform the team if a delay is imminent. Other team members should in event of a delay help out with finishing the task
	Disagreements regarding how to solve a specific problem	High	Come to an agreement by using as objective arguments as possible. If this turns out to be unsuccessful, voting will be necessary
	Not dividing large tasks into subtasks and evenly distribute these among the team members	Medium	If a member considers the workload to be too vast the member should contact the rest of the team and a new division of the tasks should be made

Category	Risk	Level	Action to Minimize
Technical risks	The assembly of the tool might be intricate and therefore too time consuming	Medium	Evaluate eventual obstacles and if these are considered too difficult to overcome, a different approach should be suggested and in turn be evaluated. Keep repeating until an agreement has been reached
	Choosing incompatible components for the tool	Low	A thorough research of the different components should be made. If such an event would occur due to bad research, the team member responsible for the component will try to solve this as efficiently as possible.
	The requirements/ suggestions from the customer might be too difficult or too time consuming to fulfill	Medium	Have a continuous conversation with the customer and if possible try to come to an agreement of whether to carry on with the specific requirement or not

H

AHP table

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**	**Weight**
1	1.00	3.00	3.00	5.00	2.00	1.00	1.50	5.00	2.50	5.00	3.00	32.00	0.19
2	0.33	1.00	1.00	1.00	0.33	0.33	0.50	1.50	0.50	2.00	1.00	9.49	0.06
3	0.33	1.00	1.00	1.00	0.33	0.33	0.50	1.50	0.50	2.00	1.00	9.49	0.06
4	0.20	1.00	1.00	1.00	0.33	0.33	0.50	1.50	0.50	2.00	1.00	9.36	0.06
5	0.50	3.03	3.03	3.03	1.00	0.70	2.00	3.50	2.00	5.00	3.00	26.79	0.16
6	1.00	3.03	3.03	3.03	1.43	1.00	3.50	4.50	2.50	5.00	3.00	31.02	0.18
7	0.67	2.00	2.00	2.00	0.50	0.29	1.00	2.00	1.00	3.00	1.00	15.45	0.09
8	0.20	0.67	0.67	0.67	0.29	0.22	0.50	1.00	0.75	1.50	1.00	7.46	0.04
9	0.40	2.00	2.00	2.00	0.50	0.40	1.00	1.33	1.00	2.00	1.00	13.63	0.08
10	0.20	0.50	0.50	0.50	0.20	0.20	0.33	0.67	0.50	1.00	0.50	5.10	0.03
11	0.33	1.00	1.00	1.00	0.33	0.33	1.00	1.00	1.00	2.00	1.00	10.00	0.06

I

Wiring Instruction

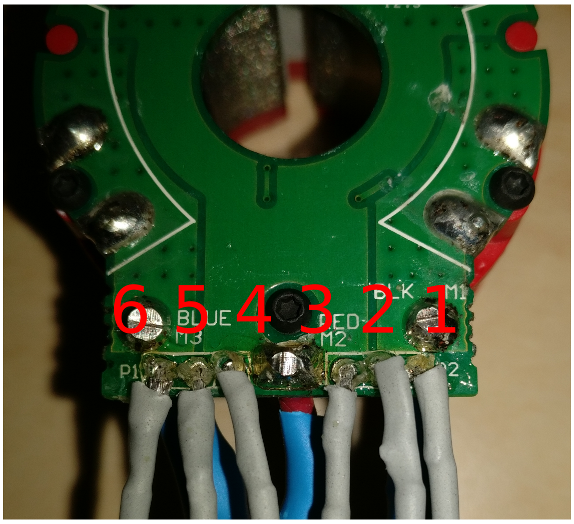


Figure I.1: Signals outputs from the stator

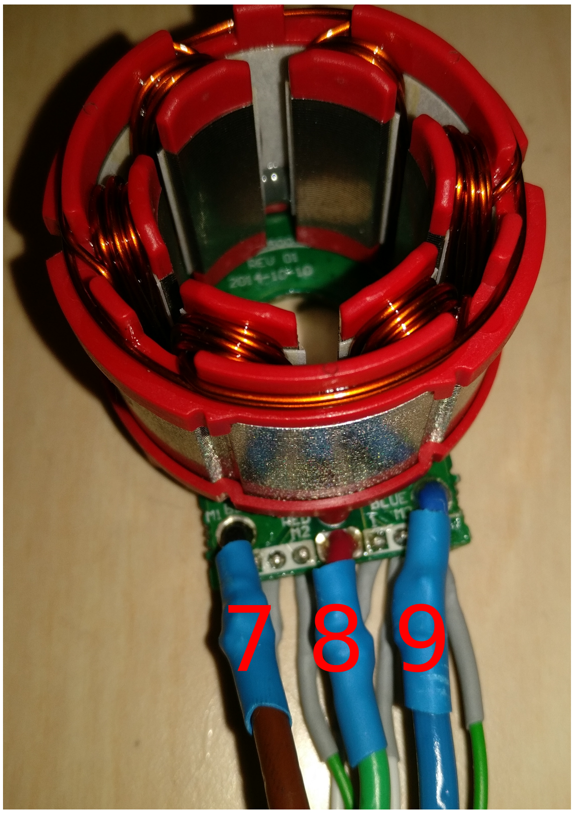


Figure I.2: Power inputs to the stator

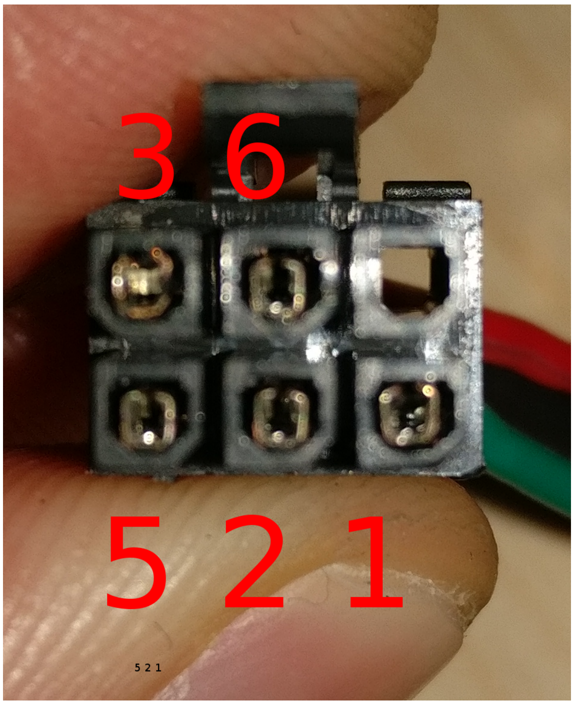


Figure I.3: Signal inputs to controller

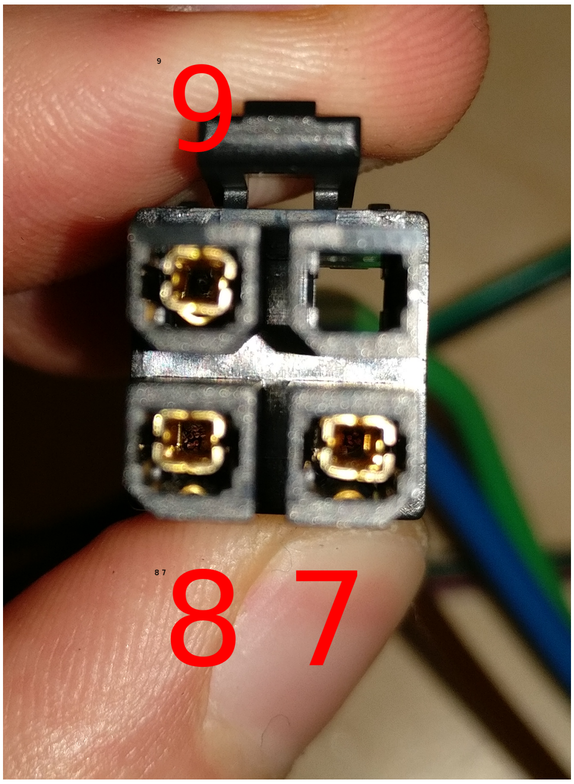


Figure I.4: Power outputs from controller

Table I.1: Wiring descriptions

Wire Number	Function Description
1	Hall effect sensor 3 signal
2	Hall effect sensor 2 signal
3	Ground
4	Shielding
5	Hall effect sensor 1 signal
6	V+
7	Motor winding 2
8	Motor winding 1
9	Motor winding 3