Design of safety system for autonomous concrete surface processing

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MASTER THESIS

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Abstract

This thesis describes the development of a safety system for a mobile robotic cell for an autonomous grinding machine. The utilization of autonomous construction equipment presents the opportunity to streamline construction processes and save time and money. This entails the development of sufficient safety equipment lowering the risk of accidents.

The goals of the project are the identification of key parameters affecting the system, the identification of a market segment for the product and a conceptual design of the safety system.

During the first phase, extensive research, interviews and testing was conducted. This acted as the basis for the creation of customer needs and product specifications. The second phase consisted of iterative concept generation resulting in the final concept, the Hydra.

The Hydra safety system is comprised of two sets of light grids and mirrors mounted on five stands creating a rectangular perimeter which detects the entry of unauthorized objects. The system has a high degree of usability allowing for quick and easy set up and take down. The system is deemed to be of interest for medium to large sized companies with experience in the industry.

Keywords: Mechanical engineering, product development, robotic cell, autonomous, floor grinding, light grid, safety

Sammanfattning

Rapporten beskriver utvecklingen av ett säkerhetssystem för en mobil robotcell till en autonom slipmaskin. Användandet av autonoma konstruktionsmaskiner möjliggör en effektivisering av konstruktionsarbetet vilket sparar både tid och pengar. Detta innebär att det även måste utvecklas effektiv säkerhetsutrustning för att minska risken för olyckor.

Målet med projektet är att identifiera de parametrar som tydligast påverkar hur systemet ska konstrueras, att identifiera ett marknadssegment för produkten samt att göra en konceptuell utformning av säkerhetssystemet.

Under projektets första fas utfördes omfattande forskning, intervjuer och testning, vilket lade grunden för både behov och produktspecifikationer. Den andra fasen bestod av en iterativ konceptgenereringsprocess som utmynnade i det slutgiltiga konceptet, Hydra.

Säkerhetssystemet Hydra utgörs av två par ljus ridåer och speglar monterade på fem stativ som tillsammans skapar en rektangulär skyddszon som kan upptäcka obehöriga objekt som rör sig in eller ut ur zonen. Systemet har en hög användarvänlighet, vilket möjliggör snabb och enkel uppsättning och nedmontering. Systemet bedöms vara intressant för företag av medel och stor storlek med erfarenhet från industrin.

Nyckelord: Maskinteknik, produktutveckling, robotcell, autonom, golvslipning, ljusridå, säkerhet

Acknowledgements

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Lastly, since this thesis marks the end or our studies, we would like to express our gratitude to all of our friends in Lund who have made our time here memorable and special. A special thanks goes out to Paulina Tengqvist for her support and encouragement throughout our studies.

Lund, January 2021

Emma Hallberg and Fabian Larhed

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Chapter 1

Introduction

1.1 Conditions for the thesis

This master thesis is a collaboration between Husqvarna Group and the Department of Design Sciences at the Faculty of Engineering, Lund University. The project is comprised of 30 hp (credits) and details the product development process of safety equipment for an autonomous grinding machine in the form of a movable robotic cell. Resources for testing, prototyping and writing are provided by Husqvarna Group and the Department of Design Sciences.

1.2 Project idea

The conceptual idea on which the project is based is a mobile robotic cell, programmed to grind the floor to the desired level using an autonomous version of a HTC grinding machine. The robotic cell should be designed to enable the user to set up and take down the cell in a short amount of time. The perimeters of the robotic cell consist of two sets of safety light curtains with one mirror each reflecting the beams, preventing unauthorized access and creating a rectangle in which the autonomous grinding machine can operate. See figure 1.1.

For this idea to work, the light curtains and mirrors have to be mounted on a structure or stand which is easy to put in place and as simple as possible to use. The main problem in designing the hardware components of the system is making the installation of the light curtains easy and intuitive while also enabling a fast set up.

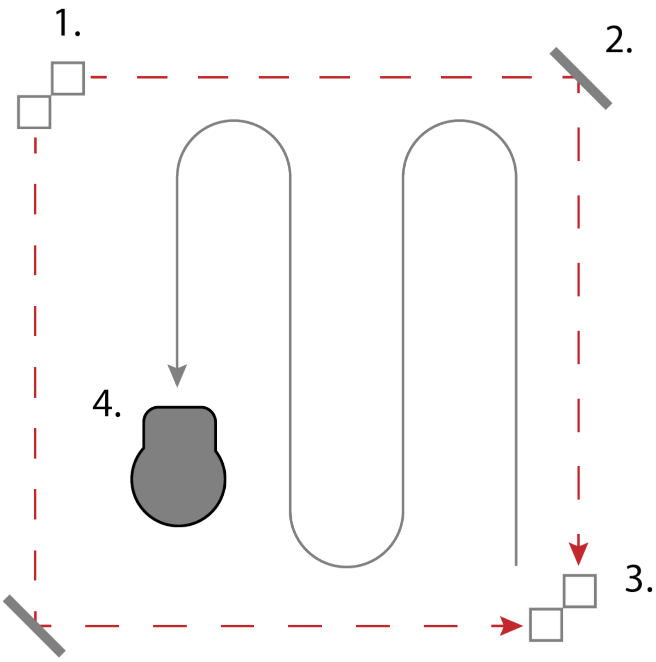

Figure 1.1: Conceptual idea of mobile robotic cell. 1. Emitter(s) 2. Mirror 3. Receiver(s) 4. Grinding machine

1.3 Research questions

The project strives to answer following research questions based upon the project idea:

- Question 1: Is it feasible to design a safety system which fulfills the needs of the system while maintaining a high degree of usability?
- Question 2: Is there a market segment for this product?
- Question 3: What are the main parameters affecting the system and how it is set up?

1.4 Delimitations

The scope of this project is to deliver a design concept that HTC can use as a base for future work. The concept shall consist of a comprehensible system-level design of the human safety and property protection sub-system. Since the concept may be subject to further change later, detail-level design of specific parts is not required.

Additionally, this means that the navigation system and the grinding system itself is not discussed in this project.

During an earlier stage in the project HTC conducted a prestudy into what safety solutions would be reasonable to further explore. Thus, this project is not required to research any different solutions than the one provided by HTC. See section 3.2 for the prestudy provided by HTC.

1.5 Autonomous machines

Autonomous machines and autonomous household appliances are rapidly making their breakthrough in society (Watson & Scheidt, 2005). The possibilities created by this technology are close to endless and may change how we view things like transportation, manual labor and more. Autonomous machines free the intended operator from controlling/monitoring the machine and enable them to do other things with their time. For home-users this freed-up time may simply be a welcome opportunity to pursue hobbies, do other chores or simply relax. For corporations, the use of autonomous machines may become a powerful tool in streamlining their operations by allowing intended machine operators to perform other value adding activities while the machine works.

In 2014, SAE International, an automotive standardization body, published a classification system for autonomous driving consisting of six levels ranging from fully manual to fully autonomous systems. The different levels as explained by Synopsys in The 6 Levels of Vehicle Autonomy Explained (2020) can be seen below. In levels 1 to 3 the human monitors the driving environment and in levels 4 to 6 the automated system monitors the driving environment.

- Level 0: No driving automation
  Manual control. All driving tasks are performed by the human.
- Level 1: Driver assistance
  The system performs one of the driving tasks by automation.
- Level 2: Partial driving automation
  The system can perform driving tasks while monitored by the human.
- Level 3: Conditional automation
  The system has environmental detection capabilities and can perform driving tasks. Human override is still required.
- Level 4: High automation

Geo-fencing is required and the system performs all driving tasks in specific conditions. Human override is possible.

- Level 5: Full automation
  Zero human interaction is necessary and the system performs all driving tasks.

Although this system is meant to describe different levels of autonomous driving it may be used in classifying other autonomous systems as well.

One of the key challenges regarding implementing autonomous machinery in any setting is safety. Sufficient safety measures must be implemented to keep the machine from damaging the people and the environment around it. These measures must be infallible and must convey to the general public how and where the machine operates.

Grinding machines are today operated at a speed of a few meters per minute and grinding large areas is time consuming. The machine operator monitors and controls the machine and is bound to the machine at all times. The time spent monitoring and operating the machine could be used for other value-adding activities at the workplace. By using a robot cell programmed to operate and grind the area without constant supervision both time and money could be saved. Due to the size and force of the grinding machine, there must be a well defined space, e.g. the robot cell, in which the machine can operate without any risk of damaging or harming the operator or the environment. Any attempt by the machine to exit or by an object, e.g a human, to enter this space unauthorized must cause the machine to power down or divert its course.

1.6 HTC and Husqvarna

The Husqvarna Group is a Swedish multinational manufacturer and developer of various outdoor power equipment as well as other consumer products. It is mostly known for its lawnmowers, chainsaws and sewing machines but also produces a big variety of other equipment for professionals and nonprofessional users.

HTC Floor Grinding Solutions, previously a part of the HTC Group AB, was acquired by Husqvarna Group's Construction division in 2017. HTC is the global market leader in floor grinding solutions. They mainly produce and develop grinding machines for different kinds of materials, with the largest segment being the grinding of concrete floors.

Chapter 2

Background

2.1 Mission statement

As a part of the pre-planning project phase a mission statement was written. The mission statement was then discussed with the company to ensure a common goal and view of the project.

The goal of the project is to design stands for two sets of ABB Orion light grids. The light grids together with two mirrors will act as a security zone which will allow the grinding machine to work inside the area without constant supervision from the operator. The operator time freed, for other activities at the workplace, is the prime benefit proposal from the project. If one operator can monitor multiple machines simultaneously the work is more efficient and both time and money will be saved.

The primary market for this product is big and experienced companies specialized in grinding and which are used to grinding large areas. The system can grind up to 225 m^2 and is the most cost and time-efficient when working on the maximum area.

Mission Statement

Product Description	• Stands for light barriers to define safety boundaries for mobile robotic cells
Benefit Proposition	• Frees operator time • Does not require constant supervision
Key Business Goals	• Safe autonomous grinding /Increased efficiency
Primary Market	• Companies doing large scale floor grinding
Secondary Market	• Entrepreneurs
Assumptions and Constraints	• Autonomous machine controlled by camera • Light grids supplied by ABB • Research and development done by HTC/Husqvarna
Stakeholders	• Operators • Sales force • Production • Service operators

2.2 The grinding process

HTC is using diamond tools to polish and grind floors of various materials. The most common material is concrete but materials such as epoxy, wood, and natural stones, etc can also be processed with HTC's tools. The goal with the grinding can be a smooth and shiny, glass looking concrete surface for malls and airports or to remove spackling paste or glue. It is also common for construction companies to grind the foundation of a new house as a part of the building process. To grind a large area is very time consuming and the machine has a speed of a few meters per minute. To get a good grinding result the surface most often needs two turns per tool and multiple tools with different grit sizes.

2.3 The machine

There are many machines of different sizes and models that can be used to grind a surface. Depending on the size of the work area, the expected quality of the result, and how much money the customer is prepared to pay different machines are used. The smaller machines are usually completely operated by the user that pushes the machine by hand, while the bigger and more heavy machines are motor-driven and controlled by an operator with a hand-control and a joystick. In this project the latter model is used.

The grinding head of the machine can be seen in 2.1. The head has discs with mounted tool holders and tools that rotate and grind the floor. The rotation in the discs comes from an electric motor which transfers the rotation onto the discs via a belt. The tool holders and the motor can be seen in 2.2. Apart from the head, the most important parts of the machine is an electrical cabinet, weights to change the grinding pressure, wheels, handle, and a panel for machine settings.

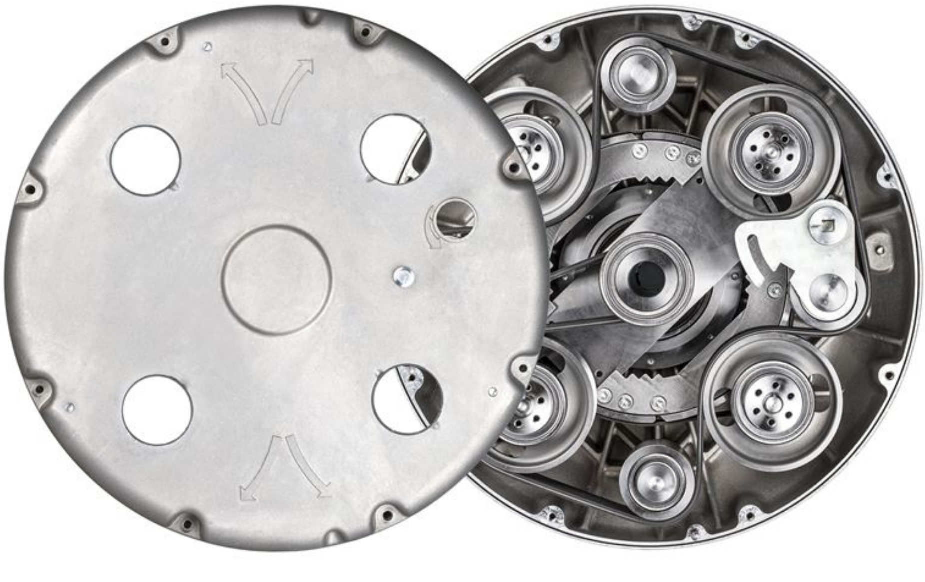

Figure 2.1: Duratiq 8 grinding head. ("HTC Duratiq 8", n.d.)

Figure 2.2: Duratiq 8. ("HTC Duratiq 8", n.d.)

Chapter 3

Theory

3.1 Existing autonomous solutions

Autonomous systems already exist in a variety of shapes and forms within people's homes, in society and in industry (Siegwart, Nourbakhsh & Scaramuzza, 2011). As an example, robotic lawn mowers have been sold since 1995 and may today be considered to be a level 2 on the autonomous scale. Similar yet different ideas are being built and implemented in construction machines such as excavators and bulldozers with the long term goal of having fully autonomous equipment. There are many systems that can be defined as autonomous and almost as many different ways to achieve that autonomy while abiding to safety regulations. Lawnmowers are smaller, more lightweight, and less hazardous than construction equipment such as bulldozers and floor grinders and require fewer safety precautions. In the case of robotic lawnmowers, most versions require the user to set up a border wire that defines the area in which the mower may operate. Border wire together with bumpers and ultrasonic sensors are enough to ensure safety for both humans and material property. In the case of construction equipment, other safety perimeters such as virtual geofencing and physical barriers are implemented to ensure safe operation.

In other scenarios, such as autonomous cleaning robots, the system needs to map/learn the space in which it will operate before performing its duties. The advantages of this approach are that there is a minimal need to adapt the working space to the system and that the operational space has no real restrictions in size. The main disadvantage is that the mapping must be done every time the system is moved to another location. The system also needs multiple sensors which makes the system very complicated and complex. For example, the autonomous cleaning robot Swingo has one lidar and

20 ultrasonic sensors (Gustavsson, Ottosson & Engman, 2020).

The main question in autonomous development is, of course, how to achieve reliable and safe autonomous driving. In relation to the previously discussed fields of autonomous equipment the safety measures needed to realize safe autonomous vehicles are major and may include technology such as artificial intelligence and machine learning combined with an array of sensors and cameras. This increase in safety needs mainly boils down to the absence of a predetermined space (of reasonable size) in which the machine or vehicle operates. Hence the problems associated with autonomous driving are made considerably smaller if the system operates within a small well-defined space.

3.2 Prestudy by HTC

An autonomous solution will face several challenges:

- Human safety - Collision, crushing, tipping over, falling, ejecting object
- Property protection - Machine, machinery, floors, worksite
- Using the system - Set up, dust handling, tools, wet grinding, multiple work areas, multiple machines, set grinding parameters

In the prestudy *Autonomous Grinder - Safety & Functionality* (2020) HTC has evaluated different methods and tools to solve the challenges in the best way possible. The tools evaluated are collision detectors, vibration and tilt sensors, object detectors, and light curtains for a secure work area.

Collision detection:
The collision detector is a bumper mounted on the machine as shown in figure 3.1. The bumper detects humans and material obstacles at floor level. Detectable obstacles include walls, expanders, and podiums. The method cannot detect any potential problems below or protruding threats above the floor level which can lead to problems.

Figure 3.1: Bumper. ("Power Bee", 2020)

Vibration and tilt sensor:
Vibration and tilt sensors as the one seen in figure 3.2 are installed inside the machine. The sensors detect abnormal vibration levels and machine tilt angles. If a problem occurs the sensors will trigger the emergency stop and stop the machine. The sensors are optimal as a complement to other safety equipment since they only react when the machine collides with an obstacle. The tilt sensor can prevent an unintentional start of the machine when the user is switching tools and the machine is in a reclined position.

Figure 3.2: Inclination sensor. ("Inclination sensor TMS/TMM88", n.d)

Object detection:
Object detection can, for example, be done with radar, camera, or lidar as the one seen in figure 3.3. Object detection can be very effective and useful for autonomous machines since they can detect all kinds of threats at various heights. Since this method is both hard to implement and expensive is it not optimal for this system.

Figure 3.3: Lidar. ("2D LiDAR sensor TiM3xx", n.d)

Secure work area:
A secure work area consists of light grids, seen in figure 3.4, and mirrors that shields the work area with ir-light beams. The grids ensure that humans don't enter and that the machine doesn't leave the designated work area. Before the system is installed the area is controlled by the user to re-insure that no threats are located inside the area. If the user is placing the grids correctly the risk of accident with humans, walls, or other external threats equals zero.

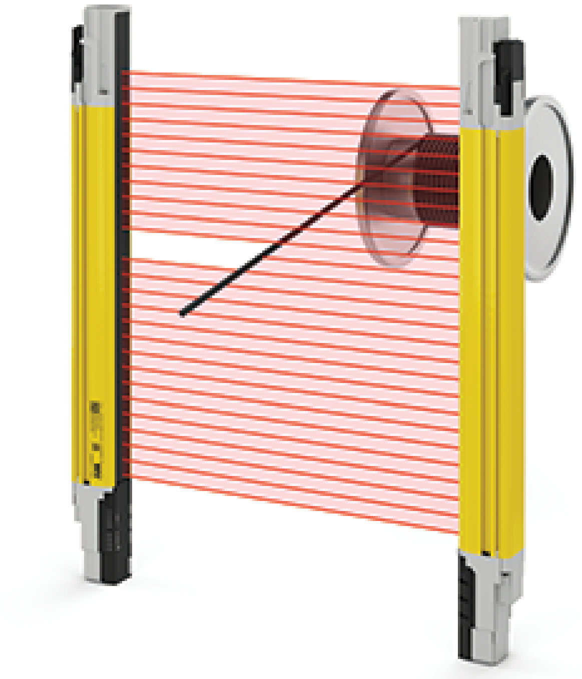

Figure 3.4: Light grid. ("Orion", n.d)

After considering all aspects the company has decided to use light grids as a security zone.

3.3 Robotic cells

A robotic cell can be described as a cell or space which contains everything a robot needs to perform a particular task. They may contain multiple robots although in this case only cells with one robot are discussed (Owen-Hill, 2017). The classic idea of a robotic cell is a single robotic arm performing repetitive tasks with high precision and is typically implemented in manufacturing lines where they can be designed to cooperate with other robots, machines or humans. However, implementation and optimization of robotic cells is a vast area and robotic cells may take many different shapes and forms (Dawande, Geismar, Sethi and Sriskandarajah, 2007).

To ensure the smooth operation of the robotic cell, safety measures must be implemented to stop foreign objects from entering the working area. Sufficient safety measures may consist of barrier guards, two-hand controls, laser scanners etc. There are many different types of barrier guards, some of which physically blocks access to the robotic cell and so called light grids.

3.3.1 Light grids

Light grids are an optical safety device, consisting of an emitter and a receiver, with the emitter sending pulses of infrared light to the receiver. If something blocks the path of the beams the light grids notifies the system and shuts potential hazards down. Most variations of light grids are equipped with between 2 and 5 infrared beams and for the curtain to work properly each beam must connect with its respective photoelectric sensor on the receiver. For the sensor to register the beam the beams angle of approach must be close to perpendicular to the receiver. Hence, it is crucial to match the emitter and receiver towards each other when installing the light grid. As illustrated in figure 5.1 this means having to control the angle in all three dimensions to successfully install the light grid.

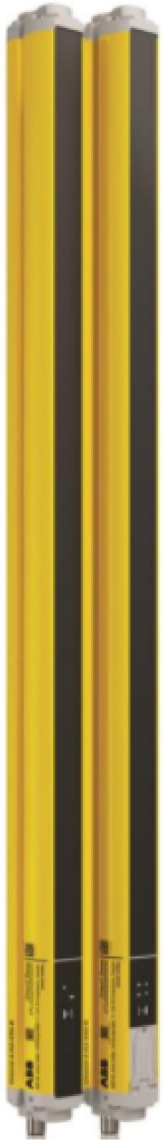

Figure 3.5: ABB Jokab Safety, 2018, Orion2 Base Safety light grids, Orion 2 Base Manual ABB rev B.

Chapter 4

Methodology

4.1 Approach

This project has been approached by combining different preexisting methods for product development. The main structure of the project is based on the methodology described by Ulrich and Eppinger in *Product Design and Development* (2012) with inspiration from the design philosophy created by Donald Norman (Norman, 2013).

4.1.1 Ulrich & Eppingers Methodology

Ulrich and Eppinger are two American researchers and writers. They carry substantial knowledge in the field of product development and have created an extensive methodology about how to approach a product development project. This methodology is summarised as a generic product development process in figure 4.1. This summation is very thorough and handles the entire process from planning to production. Because of this the process can be intimidating and contains a lot of steps which may not be necessary in a particular situation, therefore it is important that the process is reviewed during the planning of the project and parts which are not relevant are removed. This also includes adding parts deemed necessary.

This project focuses on the design parts of the process while including some of the relevant manufacturing issues and includes the steps from Planning to System-Level Design. The steps Detail Design, Testing and Refinement and Production Ramp Up has been omitted since they are beyond the scope of the project.

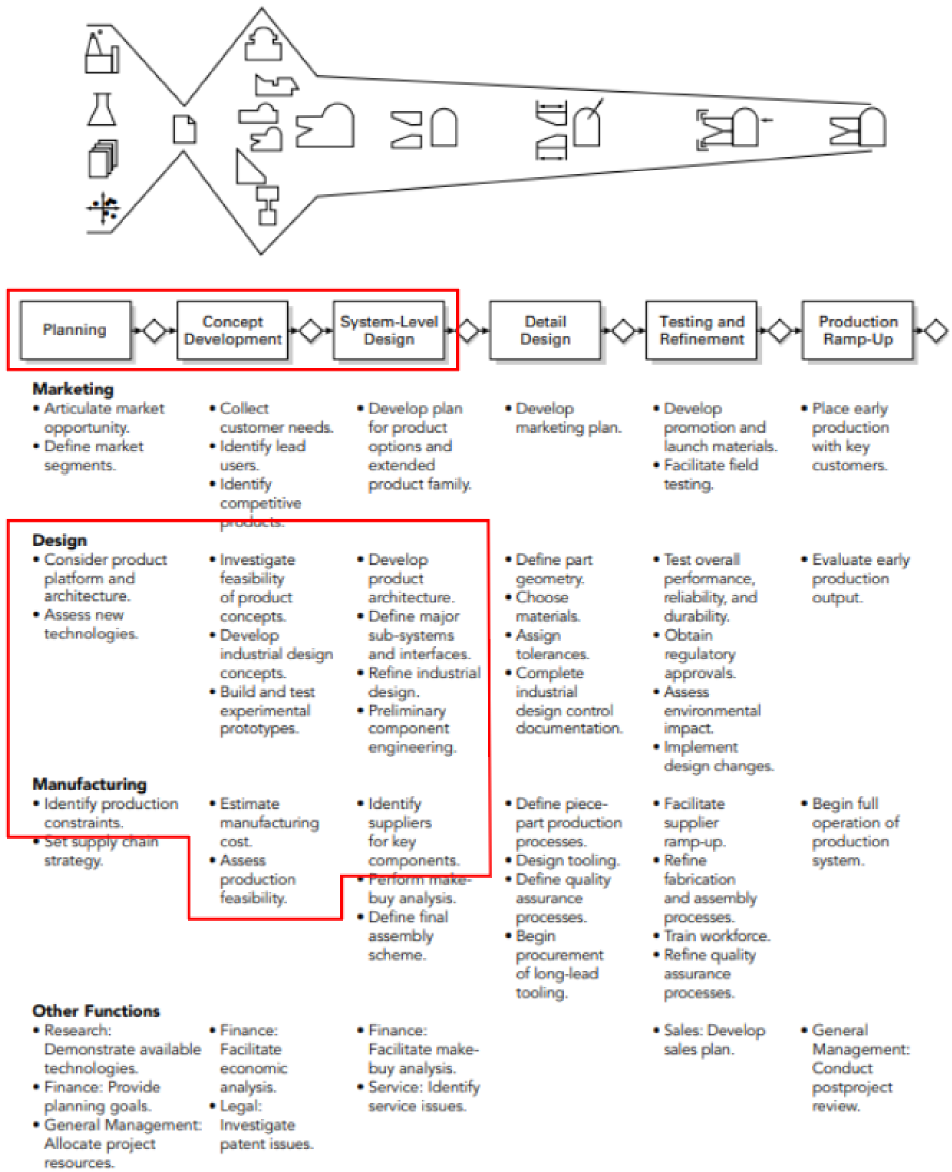

Figure 4.1: A generic product development process according to Ulrich and Eppinger. The marked areas are the parts which are utilised in the project.

4.1.2 The Double Diamond

Furthermore the shape of the project is influenced by the popular design process visualisation *The Double Diamond*. This process focuses on "diverging" and "converging thinking", where information is collected and ideas created, before being refined and narrowed down (Möller, 2015). This process can be repeated any number of times until a satisfactory result is achieved and be seen in figure 4.2 below.

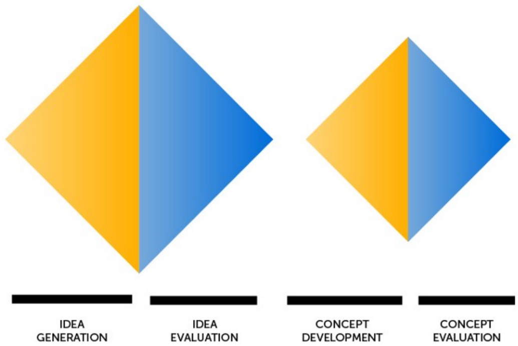

Figure 4.2: The Double Diamond design process. (Möller, 2015)

4.1.3 Iterative process

The concept development phase, seen in figure 4.3, contains the concept generation, concept selection and concept testing processes. These steps were done as an iterative process where multiple concept ideas were systematically evaluated, tested and improved upon to find the concept best suited to fulfill the product specifications. This is almost always the case in product development since new information often surfaces during the development of concepts.

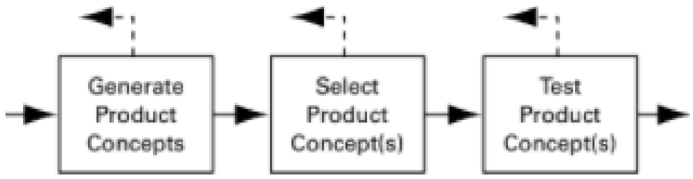

Figure 4.3: Iterative concept development illustrated by Ulrich and Eppinger with arrows going backwards. The arrows represents going through the process again with respect to new information that may have surfaced. They do not represent restarting from a blank page.

4.2 Illustration of project

The project process combines the converging and diverging shape of the double diamond with an iterative concept development which be seen in figure 4.4. This causes the research phase to be conducted as straight forward as possible while allowing the concept development phase to be repeated as many times as necessary. This is a good way to plan and conduct a small project with a strict time frame.

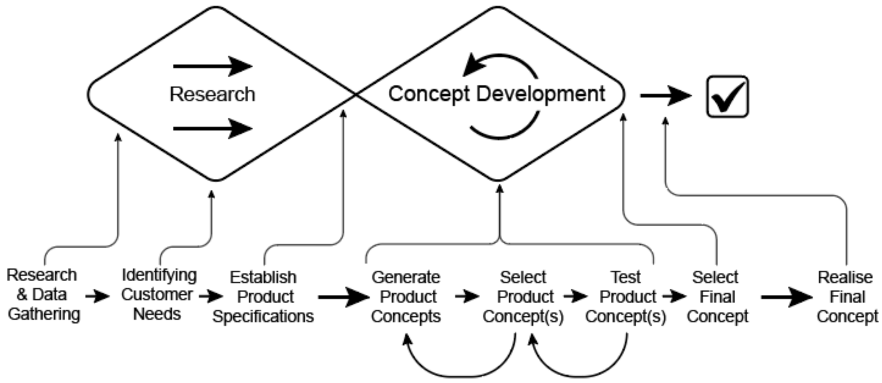

Figure 4.4: Illustration of the project process.

Chapter 5

Process

5.1 Data gathering

At the beginning of the project, HTC provided a list of important and/or necessary features and specifications which are needed for the system to work as intended. To complement these, further data gathering and identification of customer needs were necessary. This can be done by a number of techniques such as questionnaires, focus groups, interviews or observation. The main point of data gathering was to analyze and interpret the collected data to make conclusions of what the end-user wants to be included in the product.

5.1.1 Research

A review of articles and other media were made to gather information and understanding about the subject. Since autonomous construction equipment and mobile robotic cells are novel scientific fields most of the material found was located on the internet.

5.1.2 Interviews

The interviews made during the data-gathering phase can be described as open ended or unstructured. This kind of interview focuses on letting the interviewee speak freely about the subject, while being directed by a set of open questions, meaning there are no predefined format or content of the answers, planned in advance. Both the interviewee and the interviewer can steer the conversation towards any relevant subject. The person conducting the interview often utilises probing and follow up questions to further explore areas of greater interest (Preece, Rogers and Sharp, 2011).

The persons chosen for the interviews all work at HTC and can be considered as experts in the field of grinding machines who also interact with a lot of lead users in the form of prominent customers. The interviews were conducted in person or virtually with video and audio. The main points derived from the interviews are as follows:

- The system requires an operator to be able to enter the robot cell without disturbing the work flow.

This is motivated by the constant need of a floor grinding operator to be able to observe the surface being tooled/grinded and make adjustments based on the result of the tooling/grinding. If the operator is unable to do so, there is no way to ensure a satisfying result of the grinding.

- The system saves time/allows the operator to do other things

The main goal and selling point of the system. It is crucial that the implementation of the system results in a streamlined working process and the possibility for the operator to do other value adding activities.

- The system provides a satisfying grinding result

As pointed out earlier, the system needs to provide a result that the user is satisfied with. The operators usually have a lot of experience and skill within their craft and if the system can not accomplish a result similar to what the users are accustomed to they may instead choose to rely on the remote controlled or hand operated systems used today.

- Companies interested in the system are likely big and with extensive experience in the industry

The interviewees expressed strong opinions about what market segment the system catered to. The consensus was that customers interested in an autonomous system would be companies with an already established interest or use of the latest technological solutions as well as being eager to to make their operation more efficient. Companies that show these characteristics are usually medium to large sized companies with experience in the industry.

- The system is considered absolutely safe for humans and property.

The system must be able to prevent accidents and clearly communicate with the user where the system operates and which area is considered safe. There are several possible ways to do this and an important aspect of the solution is whether the user or the system should be held responsible for any damage that might occur and in which scenarios.

The interview process proved to be of critical importance to the project and for the creation of the collection of customer needs that were used to develop later product concepts and prototypes.

5.1.3 Testing

While developing a system it is important to try to understand the limits of eventual subsystems and parts of which the system is built. Since the light grids are the main subsystem in this project a number of tests evaluating the capabilities of the grids were performed. These tests were done to provide information of the physical limits of successful installation of the light grids. The maximum length, maximum angle, in all three dimensions, and maximum height difference were tested. See figure 5.1 for illustration. Worth noting is that these tests were performed with the equipment, space and knowledge available at the time. Datalogics SG Body compact (SG4-S3-080-PP-E) were used in these tests. All tests performed according to the following instructions.

- Move the light curtains to the default position.*
- Gradually increasing of the dimension being tested until the light curtain loses its connection.
- Measure the value of the dimension.

* The default position was decided by the maximum length test, which were performed first, and is as such a distance of 15 m with the light curtain mounted on vertical parallel stands.

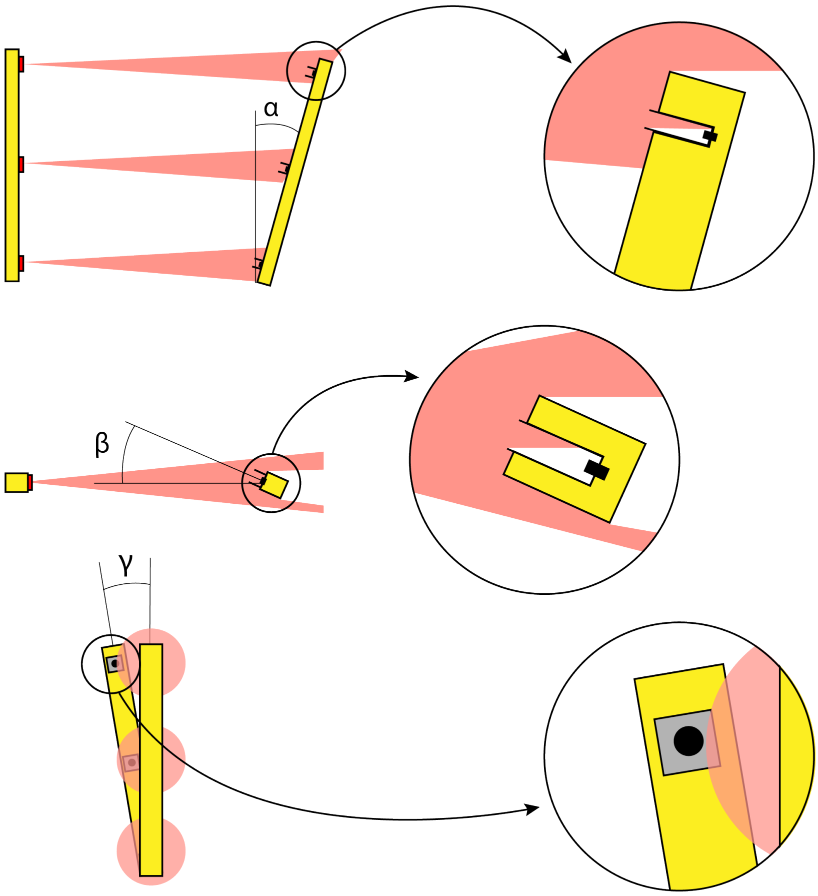

Figure 5.1: Simplified explanation of which angles must be taken into consideration and why when installing a light curtain. If the infrared beams are unable to reach all of the photoelectric sensors on the receiver the light curtain is not properly installed. α, β and γ represent the maximal angle for successful installation in each dimension

5.1.4 Results of tests

As shown by the tests, presented in table 5.1, the α and β angles of the light curtain are very sensitive, although all angles must be taken into consideration during installation. This can intuitively be explained by the amplification by distance affecting the angles of α and β and not the angle of γ.

Table 5.1: Results of tests

Dimension	Measured value	Comment
Length	15 m	Distance where successful installation is easily achieved
Height	136 mm	Maximum difference in height allowed by the testing equipment
α	0.4°	2.9° at a distance of 1 m
β	0.55°	
γ	8.8°	

5.2 Customer needs

Ulrich & Eppinger (2012) describe needs as "... largely independent of any particular product we might develop; they are not specific to the concept we eventually choose to pursue. A team should be able to identify customer needs without knowing if or how it will eventually address those needs". Because of this they differ from specifications that depend on a chosen product concept and on what is technically and/or economically feasible to do. The needs for this project both consist of needs found during the interviews with experts and needs discovered during the launch of the project and during the research. The needs are detailed in table 5.2 below.

Table 5.2: Table of customer needs derived from interviews and needs decided upon during the research and launch.

Customer needs from interviews	
The system	is easily transported
The system	is compact
The system	is ergonomic for the operator
The system	is easy to set up
The system	allows an operator to inspect the work area (while the system operates)
The system	provides a satisfying grinding result
The system	can grind large areas
The system	is easy to operate and understand
The system	is able to operate without constant supervision
The system	frees time for the operator to do other activities at the workplace
The system	is safe for users
The system	is safe for the surrounding properties
The system	is fast to set up.
Customer needs from research	
The system	can handle falls and hits
The system	protects the light barriers
The system	can be set up multiple times
The system	is inexpensive
The system	is able to combine into one bundle
The system	works outdoors
The system	provides a satisfying grinding result
The system	manages attached tubes and hoses

These needs were combined and labelled by their importance on a scale from *necessary* (3) to *useful* (1) with *important* (2) in the middle. The labeling of the relative importance of the needs are a powerful tool in the later concept generation and concept selection phase of the process when different ideas and solutions are compared based on their respective pros and cons. The labelled needs can be seen in table 5.3.

Table 5.3: Table of customer needs labelled by importance

No.		Need	Imp.
1	The system	is easily transported	2
2	The system	is compact	2
3	The system	is ergonomic for the operator	2
4	The system	can handle falls and hits	3
5	The system	allows the operator to inspect the work area	2
6	The system	provides a satisfying grinding result	2
7	The system	can grind large areas	3
8	The system	is easy to operate and understand	3
9	The system	is able to operate without constant supervision	3
10	The system	frees time for the operator to do other activities	3
11	The system	is safe for users	3
12	The system	is safe for the surrounding properties	3
13	The system	is fast to set up	3
14	The system	is easy to set up	2
15	The system	protects the light barriers	3
16	The system	can be set up multiple times	3
17	The system	is inexpensive	2
18	The system	is able to combine into one bundle	1
19	The system	works outdoors	2
20	The system	manages attached tubes and hoses	3

5.3 Product specifications

Product specifications are attempts to specify and define what a product has to do. They do not explain *how* the product will do something but *what* the product has to do in order to comply with the customer needs.

As shown in the table 5.4, one specification is often affected by several needs. Each specification has also been given a value which serves as the target for that specification, something which the product should attempt to fulfill. The process of defining specifications and connecting them to needs is another good springboard from which the leap into concept generation can be made.

The importance of the different needs was based on cost, input from HTC, feasibility, safety and by which specifications were deemed important.

Table 5.4: Table showing the target specifications

No.	Need Nos.	Metric	Imp.	Unit	Value
1	1, 2, 3, 14	Weight	2	kg	15
2	1, 2, 18	Transportation height	2	cm	100
3	1, 2, 3, 20	Maximum height	1	cm	130
4	1, 2	Maximum width	1	cm	40
5	17	Unit manufacturing cost, system	2	k SEK	100
6	17	Unit manufacturing cost, stand	2	k SEK	1,5
7	1, 2, 10, 18	Ease of transportation	2	Subj.	
8	1, 3, 8, 9, 11,13, 14, 18, 20	Usability	3	Subj.	
9	7, 10	Grinding area	2	m^2	225
10	5, 6, 10, 12	Result of grinding	3	Subj.	
11	5, 6	Possibility to enter	3	Binary	Yes
12	9, 10, 11, 12	Autonomy	3	Level	4
13	5, 9, 10, 11, 12, 20	Errors	2	Number	0
14	4, 9, 10, 13	Operator time saved	3	%	70
15	3, 8, 11	Accidents with users	3	Number	0
16	12	Accidents with surroundings	3	Number	0
17	2, 3, 8, 13, 14, 16	Setup time	3	Min.	15
18	4, 15	Impacts to failure	2	Number	200
19	4, 14, 15	Setups to failure	2	Cycles	2000
20	18	Pieces for transportation	1	Qty.	1
21	19	Water resistance	2	IP Code	IP65
22	4, 11, 19	Tipping point	2	Degrees	25
23	11, 12, 19	Light disturbance	1	Binary	Pass
24	6, 12	Maximum distance to wall	3	cm	10

5.4 Subproblems

Based on the customer needs and requirement specification the most important subproblems to solve in the product are identified. The solutions to the subproblems are then combined into different concepts and used in the development process.

The seven most important subproblems to solve in the stand are as follows:

The bottom plate:
The bottom plate or the foot of the stand. This subproblem includes everything that the stand stands on or that stabilizes the stand.

The post:

The post of the stand. This subproblem includes the look and shape of the post and fastening of the light grid.

The fastening mechanism for laser pointer:
This subproblem includes the look, function and placement of the fastening of the laser pointer.

Transportation:
Transportation and adjustments of the stand for transportation. This includes both transportations to another workplace and transport of the stand by hand to a new work area.

The height adjustment:
This subproblem includes the adjustment of the height of the stand for the configuration of the light grids and transportation.

The light grid configuration:
This subproblem includes the configuration and the adjustment of the mirrors and light grids to activate the safety cell.

The feedback system:
This subproblem includes the feedback of the system such as indicators if the light grids are connected, muted or other problems with the system.

5.5 Solutions to subproblems

During the brainstorms and discussions made in the project were a variety of solutions to the subproblems discovered. Below are the solutions and requirements from those brainstorms listed.

The bottom plate:
The bottom plate needs to stand stable on all types of floors including uneven floors and floors with great height difference. The bottom plate also needs to provide enough weight so the stand is hard to knock over and so the stand is not affected by vibrations from the machine or other external impacts.

- Door holder: A supporting leg based on the design of a door holder with a built in spring. The legs can be placed in an upright position when not used or when the stand is placed close to a wall or corner. The folding feature makes the bottom plate flexible and grinding close to walls possible.

- L-shaped bottom plate: A L-shaped bottom plate for grinding close to corners and walls.

- Extra weight: Extra weight that can be mounted on the bottom plate when grinding outside in wind.
- Wheels: Wheels on the bottom plate for increased movability and more ergonomic transportation.

The post:
The post needs to stand straight in both vertical and horizontal direction and have the same height as the other stands for configuration of the light grids. The light grids are not removable for transportation and the fastening mechanism depends on the choice of adjustment method. The profile of the post is either a modular solution that can be used for both the light grids and the mirrors or two separate profiles. A modular solution would just require the purchase and production of one part but the part would be more complex and therefore slightly more expensive than two simpler profiles.

- A rectangular profile for light grids and a flat profile for mirrors.
- Removable bottom plate.
- Fastening mechanism for the light grid.
  - Post-processed holes for fastening with screws.
  - Fastening with plates without post-processed holes.
- Modular solution
  - L-shaped profile with holes for light grids on the outside of the L and place for the mirror on the opposite side.
  - L-shaped profile with holes for light grids on the inside of the L and place for the mirror on the same side.

The fastening mechanism for the laser:
The fastening mechanism for the laser pointer is placed above the light grid or mirror to make it more visible for the user. The laser needs to be easy to remove and able to use on all stands. The fastening mechanism also needs to be able to handle hits and falls and protect the laser.

- Slide the laser into a slot in the profile.
- Fastened on top of the light grid with a fastening in the shape of a “hat”.

Transportation:
The stand needs to be as easy as possible to transport both between workplaces and on the site. It also needs to be ergonomic for the user and not exceed the maximum weight to carry according to Swedish law. It is also desirable with a stand as compact as possible to save space during transportation.

- Wheels for transportation between working areas at the site. With wheels are heavy lifts avoided.
- Handle on the stand for more ergonomic lifts.
- Removable bottom plate for a more compact and flexible stand.

The height adjustment:
It is crucial for the configuration of the light grids that the height of the grids is able to alter. The height can be altered on either the bottom plate, on the post or by moving the light grid.

- The post:
  - "Crutch" mechanism.
  - Gas spring.
- Light grid:
  - Slide the light grid in a rubber reinforced slot in the profile for high friction.
  - "Armrest" mechanism from an office chair.
  - Hand wheel that controls a mechanical solution moving the grid.
- Bottom plate:
  - Screws to adjust height and stability.

The light grid configuration:
To configure the light grids adjustments in all directions must be possible. A spirit level is installed on the stand to ensure that the stand is straight both vertically and horizontally.

- Screws in the bottom plate and ball joint in the post.
- External ball joint.
- Internal ball joint in the bottom plate.

- Screws in the bottom plate.
- Adjustment around the posts' shoulder.
- Integrated measure tape in the post to indicate the maximum distance between stands.
- A laser with a measuring feature to indicate the maximum distance between stands.
- Flexible fastening of the light grid on a non-adjustable stand. The position of the light grid is adjusted for configuration.

The feedback system:
The feedback system needs to be both easy to understand and see from different angles and distances. The light that indicates configuration on the light grid is today placed at the bottom of the grid and is hard to see from the maximum distance. The goal with the feedback system is to clearly indicate if the system is up and running, muted or if an error occurs.

- On the light grid and mirror stand:
  - A green light when the light grids are configurated
- On camera stand:
  - A green light when the light grids are configurated
  - A Red light when the light grids are muted
  - A Yellow light when the system is on but not configurated

5.6 Concept generation

5.6.1 Early concepts

This section contains a quick overview of the earliest concept ideas, based upon the product specifications, the subproblems and the solution to the subproblems presented in section 5.3, 5.4 and 5.5. As concepts, these do not contain any information about details such as dimensions, manufacturing methods or specific shapes of components.

Concept 1:
Concept 1 consists of a removable and foldable foot with three wheels, similar to the wheels used on shopping carts, for easier and more ergonomic transportation. The light grid is removable and attached to the stand with two click-attachments which can be seen in figure 5.2. A 15-meter long tape measure is integrated into the stand for placement of the stands and measure of the work-space. A lamp is installed on the top, turning green when the light grid is in contact with the receiving stand.

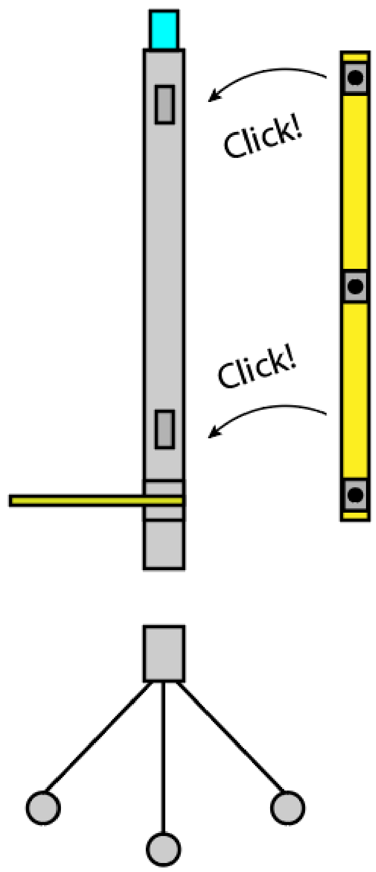

Figure 5.2: Illustration of concept 1.

Concept 2:
The stand in concept 2 is collapsable and the height can be altered for transportation. The height is altered when the inner tube slides inside the outer tube. The light curtain is connected to the stand in two points in the upper part of the curtain to minimize the height. A handle is also mounted on the side of the stand for easier and more ergonomic lifting and transportation. Concept 2 is illustrated in figure 5.3.

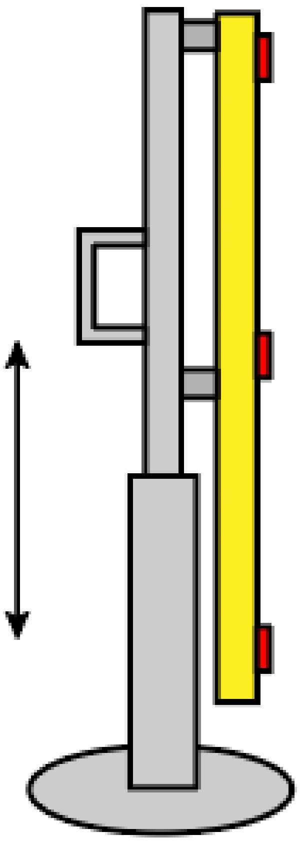

Figure 5.3: Illustration of concept 2

Concept 3:
The height of the stand in concept 3 cannot be altered for transportation. The bottom plate is shaped like a cross with foldable joints as can be seen in figure 5.4. This feature can minimize the size of the bottom plate for transportation and give the customer the ability to customize the size of the bottom plate when grinding close to corners and walls. A laser pointer is mounted on the stand to help align the emitter, receiver, and mirror stand.

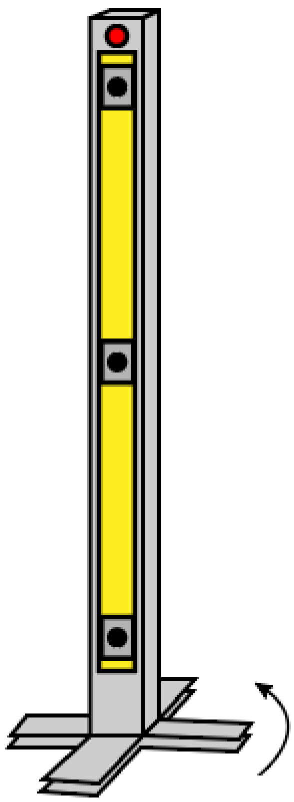

Figure 5.4: Illustration of concept 3

Concept 4:
Concept 4 has a solid bottom plate with removable post and marked crannies for laser alignment of stands. Pieces of equipment such as optics and mirrors can be removed due to them being fastened by metal bands tightened by screws.

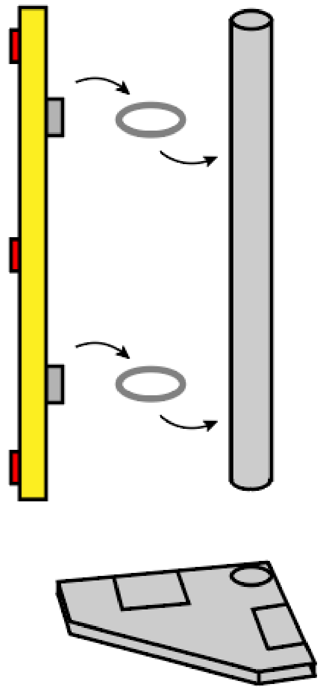

Figure 5.5: Illustration of concept 4

Concept 5:
Solid bottom plate with a foldable post containing string-handles inside. The handle will appear when the stand is in its folded transport layout for more ergonomic lifts and can be seen in figure 5.6. The equipment must be removed prior to folding. A measuring tape is integrated into the stand.

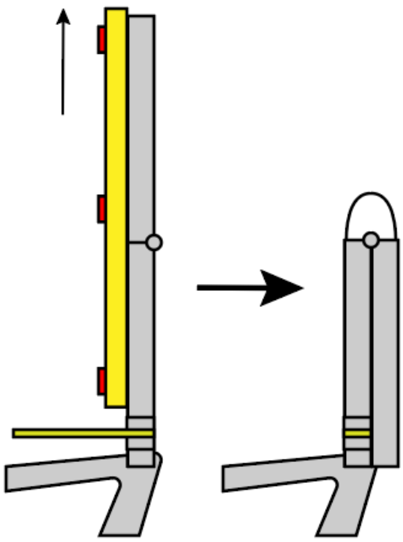

Figure 5.6: Illustration of concept 5

Concept 6:
Rigid construction with integrated wheels for easy placement and transportation. The wheels are placed on the upper side of the bottom plate so as to not tilt the plate/stand while in use. Possible handle placed at the top for easy transportation with the wheels and can be seen in figure 5.7. Not foldable in any way.

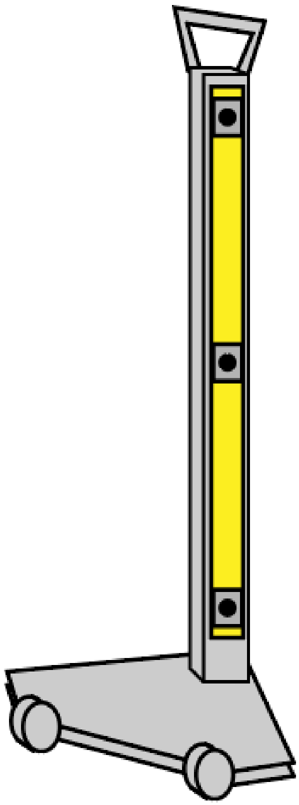

Figure 5.7: Illustration of concept 6

The most interesting ideas to continue to develop from the early concepts:

- Lamp to clearly show if the sender and receiver are connected.
- Integrated tape measure
- Wheels on bottom plate
- Handle on post
- Portable laser
- Bottom plate shaped for corners

5.6.2 Second concepts

The two concepts presented in this section have been extensively thought through and combines the ideas from the early concepts with new ideas and requirements, listed below, which have surfaced parallel to the concept generation.

Additional information taken into consideration:

- Door holder/Spring mechanism for folding leg
- Implement flexibility in the solution
- L-shaped profile with indentations for light grids.
- Plastic cover for the electronics to protect it from dust, water, etc.
- Implementation of a target point for the laser pointer.
- Adjustments on the bottom plate to straighten up the stand may be necessary.

Modular profiles

Both of these concepts implements modular aluminium profiles onto which both mirrors and light grids can be mounted, allowing the profile to be used in all of the stands and thus lowering manufacturing costs. The profiles are designed to act as both the main structure of the stand and as protection for the light grids.

Concept X

Profile:
Concept X is a stand with a modular cover for the light grids. The cover can be used for both the grids and the mirror depending on the type of stand. As can be seen in image 5.8 the yellow grids are placed at 90 degrees relative to each other with the

blue mirror on the opposite side. The cover will protect the grids and mirror from damages caused by the machine, falls, or other impacts.

Bottom plate:
The stand has a small quadratic bottom plate with four support-legs inspired by a door holder. The idea behind this solution is to minimize the floor-space required and to make it as flexible as possible. If the stand is placed in a corner the two corner-legs can be folded-up and the stand is thereby placed closer to the corner. The same can be done in connection to a wall or other obstacle where one or several legs can be folded up if needed. The legs will also stabilize the stand and keep it straight in the vertical and horizontal direction. Two wheels are mounted on the side of the bottom plate and are not included in the model in image 5.8.

Light grid configuration:
The grids are adjustable and can be moved up, down, and around its shoulder without adjusting the stand itself. This gives the stand more flexibility when configuring the light grids and makes the grids not dependent on each other. Numerous tests have shown that the angle and position of the grid around its shoulder is the most important for the configuration. A error in the angle will be amplified by the distance and become a big error on 30 meters of distance and thus decrease the chance of successful configuration drastically.

A handle is placed on the top of the stand for transportation and is not included in the model in image 5.8.

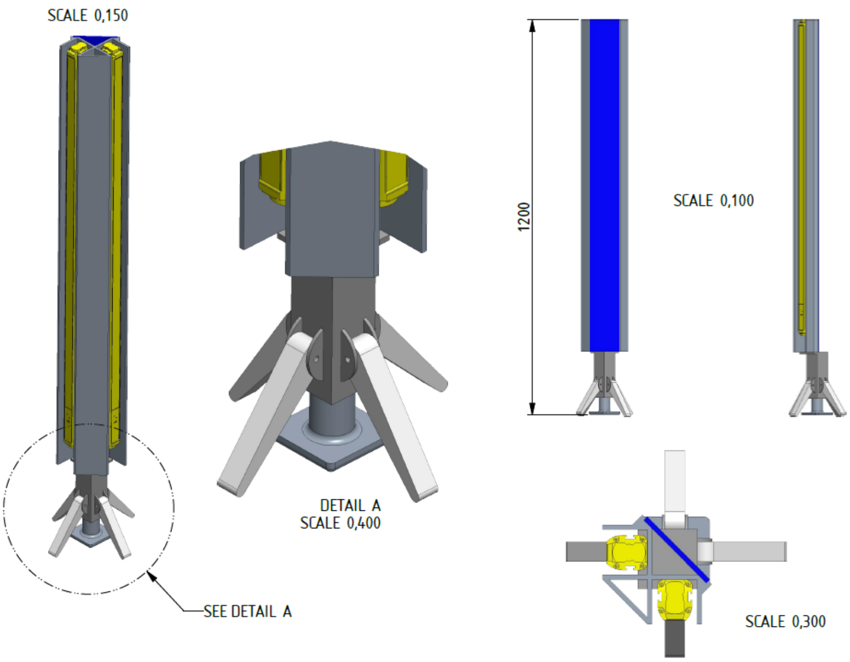

Figure 5.8: Illustration of concept X showing both the mounted mirror in blue and the mounted light grids in yellow. The illustration also shows the aluminium profile and the support legs. Naturally, the mirror and light grids are not to be mounted on the same stand, this is done to illustrate the modular profile.

Concept Y

Profile:
Concept Y has, just as concept X a modular cover to protect the grids and the mirror. Instead of placing the grids outside of the profile as in concept X are the grids placed inside the profile at 90 degrees relative to each other.

Bottom plate:
The bottom plate is an L-shaped plate with two wheels mounted on the side. The L-shape will allow placement close to walls and minimize the space needed in corners. To ensure that the stand is straight both vertically and horizontally are screws mounted in the bottom plate to higher or lower it to the correct position. The screws can also be used to adjust the height of the grid so the height of the sender and receiver are the same. A ball joint is integrated into the bottom plate for flexible adjustment of the grinds.

Light grid configuration, the ball joint:
The ball joint is mounted into the bottom plate and can be seen in detail view A in image 5.9. The ball joint will enable flexible adjustment of the post and grids in all directions including a height altering mechanism implemented in the rod connecting the ball joint to the profile. When the user is setting up the system the ball joint is loosened and the grid can be moved around freely. When contact is established the user locks the ball joint again and the system is ready to use.

A handle is placed on top of the stand for transportation and adjustments and is not included in the model in image 5.9.

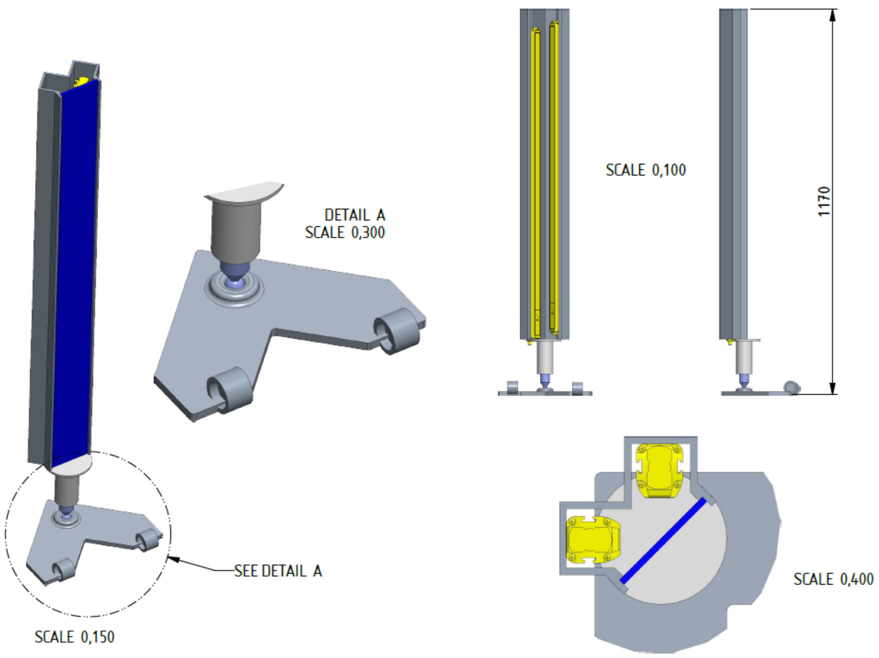

Figure 5.9: Illustration of concept Y showing both the mounted mirror in blue and the mounted light grids in yellow. The illustration also shows the aluminium profile, the ball joint and the bottom plate with attached wheels. Naturally, the mirror and light grids are not to be mounted on the same stand, this is only done to illustrate the modular profile.

Both concept X and concept Y are focused on allowing the user to easily adjust all necessary parameters required to successfully establish contact between the emitting and receiving stands. Figure 5.10 below shows the different points of movement in concept X and Y. After testing the different ways of moving and adjusting the light grids it was decided to continue developing a modified version of concept Y. This was mainly decided based on the usability of the ball joint as well as the difficulty in establishing contact with both light grid locked to the stand, as were the case in concept X.

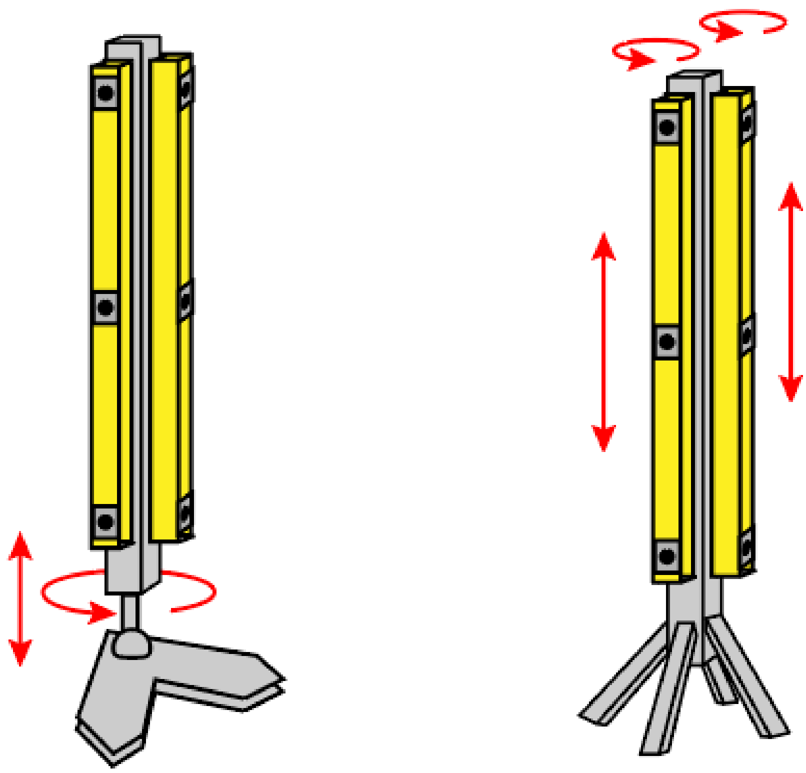

Figure 5.10: Illustration of different points of movement in concept X and Y. Concept Y utilises a single point for height control and a single point for adjustment of all angles while concept X has individual height and axial angle control of each light curtain.

5.6.3 Concept Y 2.0

Concept Y 2.0 is an improvement of concept Y and utilises the same ball joint as concept Y but only on the receiving stand. Furthermore the receiving stand is split into two separate stands, one for each receiving light grid, with one ball joint each. The mirror stands and the emitting stand are instead mounted on a pin with free movement around the axis.

Profile:
The aluminum profile utilised in the mirror and sending stands is of a similar modular design to those in concept Y while the receiving stand omits any kind of stabilizing profile and instead mounts the light grids straight onto the platform of the ball joint. This makes the stand easier to adjust, transport and allows for a handle to be placed directly on top of the receiving light grid, the downside to this is that the light grid does not have any protection from hits or bumps.

Bottom plate:
The bottom plates of all stands in concept Y 2.0 are similar to the one shown in concept Y complete with screws for height adjustment and wheels for easy transportation.

Light grid configuration, the ball joint:
With only one ball joint per pair of light grids and the ability to move the receiving light curtains individually this system provides the user with an easier to understand and more flexible solution than the earlier concepts. Since the emitting and mirror stands both have a fixed vertical position the only stand that needs to be finely tuned in is the receiving stand. This is combined with a vertical laser marking the approximate path of the IR beams for easier installment.

Targets for laser:
Concept Y 2.0 also features target areas on the mirror stands and the receiving stands for the laser mounted on the emitting stand. The targets act as guides for positioning the receiving stand by allowing the user to know at which relative angle the laser, and by extension the infra red beams, have towards the mirror and the receiving light grid. The targets are mounted on the top of both receiving light grids and both mirrors. A illustration of the working principle of the targets can be seen in figure 5.11.

Successful user tests were performed on concept Y 2.0, causing the concept to act as a base for the final concept. Details about user tests in section 5.7.

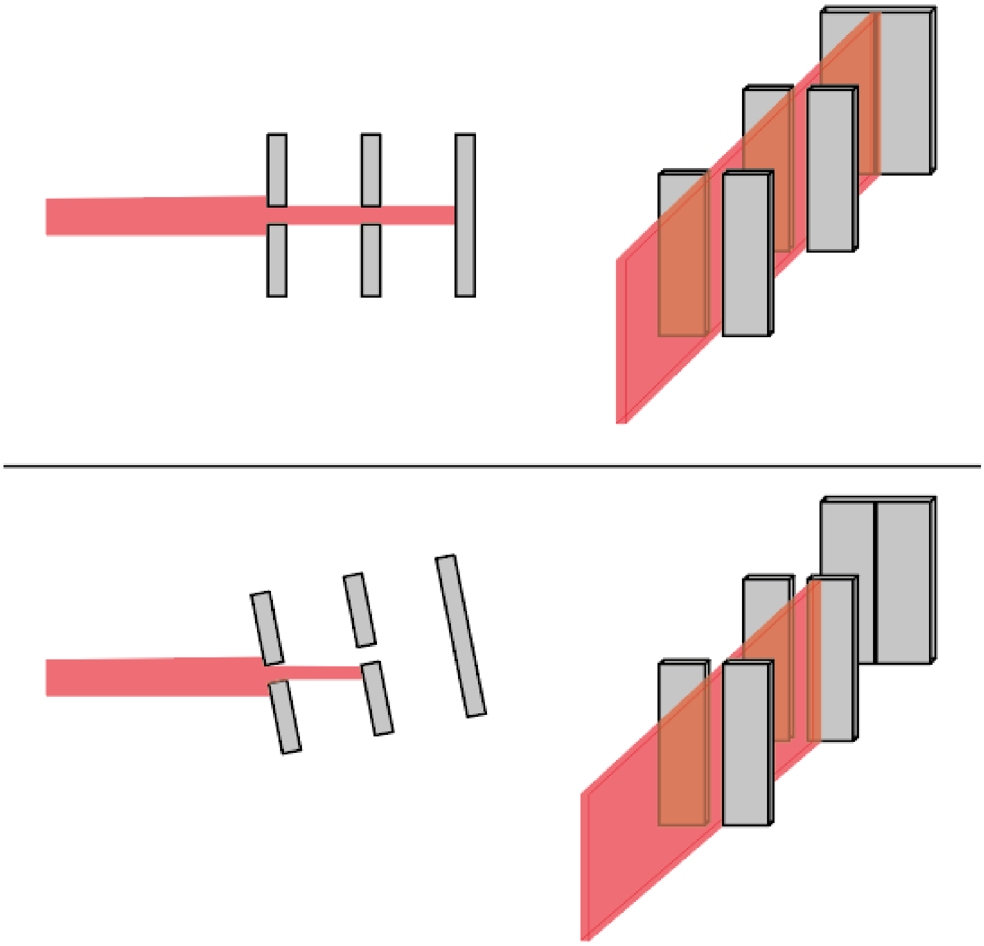

Figure 5.11: Conceptual illustration of the working principle of the targets for the laser. When the laser hits the black line on the last plate the receiver is correctly placed in regard to the β angle. (See figure 5.1 for reference)

5.6.4 Final concept

The final concept implements feedback and information gathered during the user tests performed on concept Y 2.0 which is further discussed in section 5.7. It follows the same outline as concept Y 2.0 but implements changes in the placement of the lasers, laser targets and protection of the light grids as well as changes to the bottom plates and aluminum profiles. It also details the placement of handles, the locking mechanism for the ball joint and possible batteries on the receiving stand.

Profiles:
The final concept utilises a reworked aluminum profile for the emitting and mirror stands and a new u-profile for the receiving stand. The u-profile is implemented as protection in the event of the receiving stand falling over.

Bottom plate:
This concept features different bottom plates for the receiving stands and the other stands. The bottom plates have been reworked to better fit into corners while not interfering with the operation of the grinding machine.

Light grid configuration, the ball joint:
The configuration and installment of the light grids are done in the same fashion as in concept Y 2.0. The locking of the ball joint is performed with a pedal placed on the bottom plate of each of the receiving stands.

Targets for laser:
The targets for the laser are placed inside of the profiles and are thus better protected from falls and hits than in earlier concepts.

Detailed drawings, illustrations and information about the final concept is presented in chapter 6, section 6.2.

5.7 User test

To evaluate and get feedback from users a user test was performed. The goal of the test was to see how intuitive the stand and the different features are for someone without preexisting knowledge of the product. A goal was also to get feedback on the prototype and the whole system that can lead to improvements on the final product.

The test was a combination of an observational study and a questionnaire. Observations are a good method to gather data and can show more nuances than other methods(Preece, Rogers and Sharp, 2011). A risk with observations is that a lot of data is gathered which is hard to analyze and may not be relevant for the process. To avoid this a complementary questionnaire was used to provide data and ideas from the test subjects. The questionnaire with answers from the test users can be seen in appendix C.

The test was divided into two parts, one where the test subject should set up the system and establish contact between the grids with a short introduction and one with a longer, more thorough description. The test was done on nine test users with limited preknowledge of the product and the industry. The test subjects had never used a similar product or a floor grinder.

The test surface was around 8x8 meters, which is around half of the target surface 15x15 meters. The decision to choose a smaller test area was made to make it easier for the test subject to get contact between the grids and to test the prototype, not the grids. To save time and eliminate unnecessary moments the sending stand was placed at a correct position and the distance between the mirror stand and the receiving stand measured in advance. The test was also done on one pair of grids and not the full system. Also this to save time and make the test smoother to implement.

During the first part of the test, the test subject received basic instructions about the test, the light grids, and the system. The user were then instructed to move the mirror and the receiving prototype stand to correct positions and to establish contact between the light grids. When contact was achieved, the test subject gave up or ten minutes had passed the first part of the test was ended. Before the second part of the test all features, such as the lasers and the appurtenant targets on the prototype stand and the mirror stand was explained and demonstrated to the test subjects. The test subjects also got tips and information about which angles are the most sensitive. The additional information was given to see if the test subjects thought it was easier to set up the security zone with help from lasers targets etc or if it doesn't affect the experience of the difficulty of the test. The second part of the test consisted of the same elements as the first and was also ended after contact, five minutes or the test subject gave up. After the test, the test subjects filled in a form with questions about their experience, the different features, the prototype, and give feedback on the test and the system. The form included open questions so the users could contribute with ideas as well as multiple-choice questions. This to get as useful feedback as possible for future improvements. The users were encouraged to give feedback both during and after the test.

Chapter 6

Result

The main result of this project is the creation of a system-level design that provides a satisfactory solution to the project idea and research questions presented in chapter 1. This chapter will present the final design of the system, results on which the final concept is based as well as additional results derived from experiments and research which may be of use when realizing the concept.

6.1 Results from tests

Data and feedback gathered during the user tests were a crucial part of the decision making leading up to the finished concept.

A majority of the test subjects thought that the hardest part of the test was to achieve contact between the emitting and the receiving light grid. The contact zone is limited and small angular movements of the prototype stand, the mirror, and the laser results in big errors on 30 meters.

Six out of nine test subjects thought that the degree of difficulty to connect the stands was medium to easy. Two users rated the simplicity as low. These users could not successfully connect the light grids during either test 1 or 2. After these tests a laser error was discovered. The laser beam didn't match the ir-beams and indicated the wrong position for the prototype stand. After the laser was fixed it was easier to configure the stands again.

The laser and laser targets were the parts of the concept which received most appreciation during the test. The movability of the prototype also received positive feedback.

The most common feedback expressed about changes or additions to be made to the system was for the system to give the user more feedback. More and more detailed feedback would help the user to see which parameters to change to achieve successful contact between the light grids. As an example some of the users wanted feedback on which direction the stands were to be moved if connection was not established. Multiple users also wished for a more concentrated and sharp laser beam. The laser used during the test got very wide after being reflected in the mirror, which made it hard to know where the middle of the beam was. One user also requested a feature on the prototype stand to see where the laser is when it's not on the stand, like some kind of portable wall.

The ball joint also got positive feedback. Seven out of nine users rated the ball joint as easy to use. Other feedback on the ball joint was that more friction would facilitate the use and that a possibility to lock the joint in different directions could be helpful.

Main results from user tests:

- Establishing connection between the light grids is perceived as the most difficult part of using the system.
- Implementation of more feedback for the user would increase the systems usability
- The system would benefit from a better laser with a more focused and more well defined beam
- More friction in the ball joint may help the user achieve a successful connection
- Better precision in laser targets and laser placement is needed for the system to work as desired
- Easy movement of the system is important.

6.2 Hydra concept

The resulting final concept has been named the Hydra after the multi-headed monster from the Greek and Roman mythology. This section provides a detailed description of the Hydra concept, the different subsystems and parts it is comprised of and how it implements the results from the testing.

6.2.1 Overview

The system is built around the conceptual idea presented in chapter 1, with two sets of light grids mounted on two movable stands. The light grids are reflected in mirrors mounted on separate stands, creating a rectangular zone in which the grinding machine can operate safely. The safety zone can be seen in figure 6.1 and 6.2.

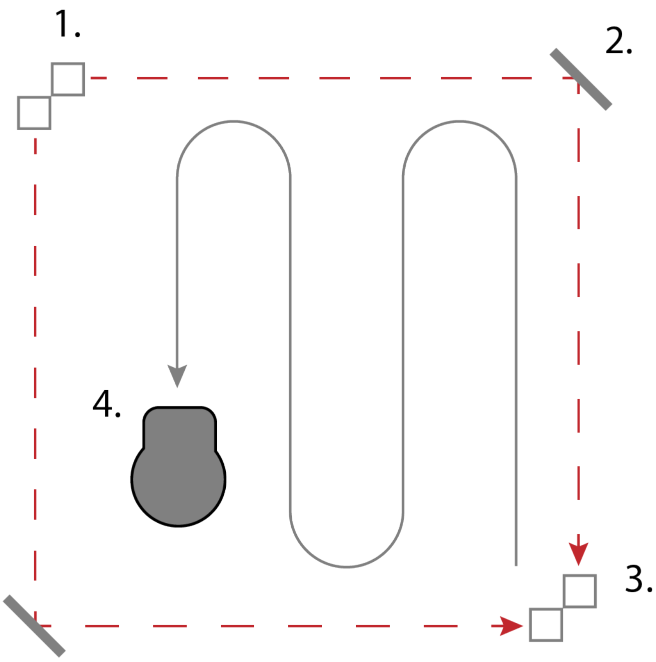

Figure 6.1: Conceptual idea of mobile robotic cell. 1. Emitter(s) 2. Mirror 3. Receiver(s) 4. Grinding machine

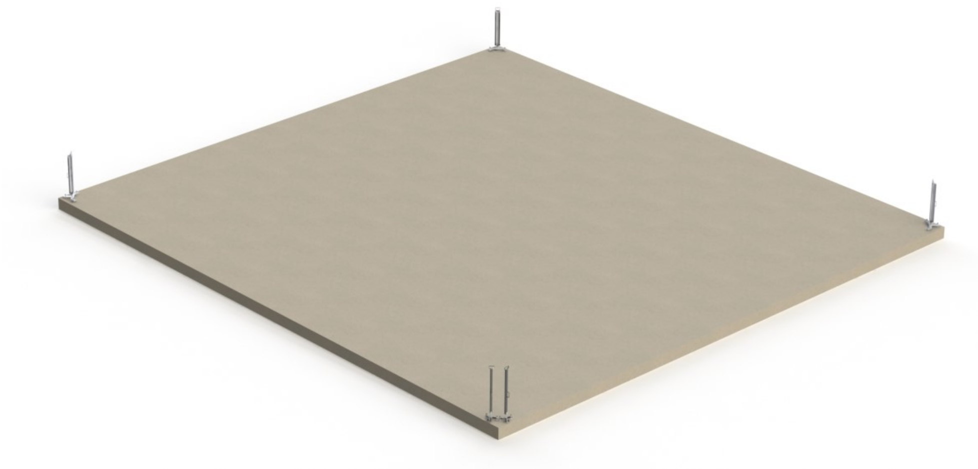

Figure 6.2: Grinding area with system

As explained above, the system is built around four different stands: the emitting stand, the two mirror stands and the receiving stand. Of these four, the emitting stand and the mirror stands are based upon the same modular base design, with the only difference being the mounting of either emitting light grids and lasers or mirrors and laser targets separating them. The receiving stand is split into two separate stands, with one receiving light grid mounted on each. Hence, the system is really comprised of 5 stands although the receiving stands can be viewed as one entity.

6.2.2 Emitting and mirror stands

The main component of the emitting and mirror stands are an extruded aluminum profile, shown in figure 6.9 designed for allowing both mirrors and emitting light grids to be attached. A plastic cover is mounted in place of the mirror on the emitting stand. The cover acts as protection for cables and electronics connected to the light grids and lasers. Attached to the top and side of the profile are two handles for transportation and adjustment of the stands which can be seen in figure 6.7. The profile is mounted on top of a pin allowing 90 degrees of movement. The pin is connected to a flat bottom plate or foot which serves as the base of the stand. The foot is designed to allow easy access to corners and is equipped with wheels mounted to the front for easy transportation. The foot rests on three base jacks or screws with which the height and angle of the foot can be controlled to account for placement on uneven ground. The emitting stand can be seen in figure 6.3 and figure 6.4 and the mirror stand in figure 6.5.

Figure 6.3: Sending stand

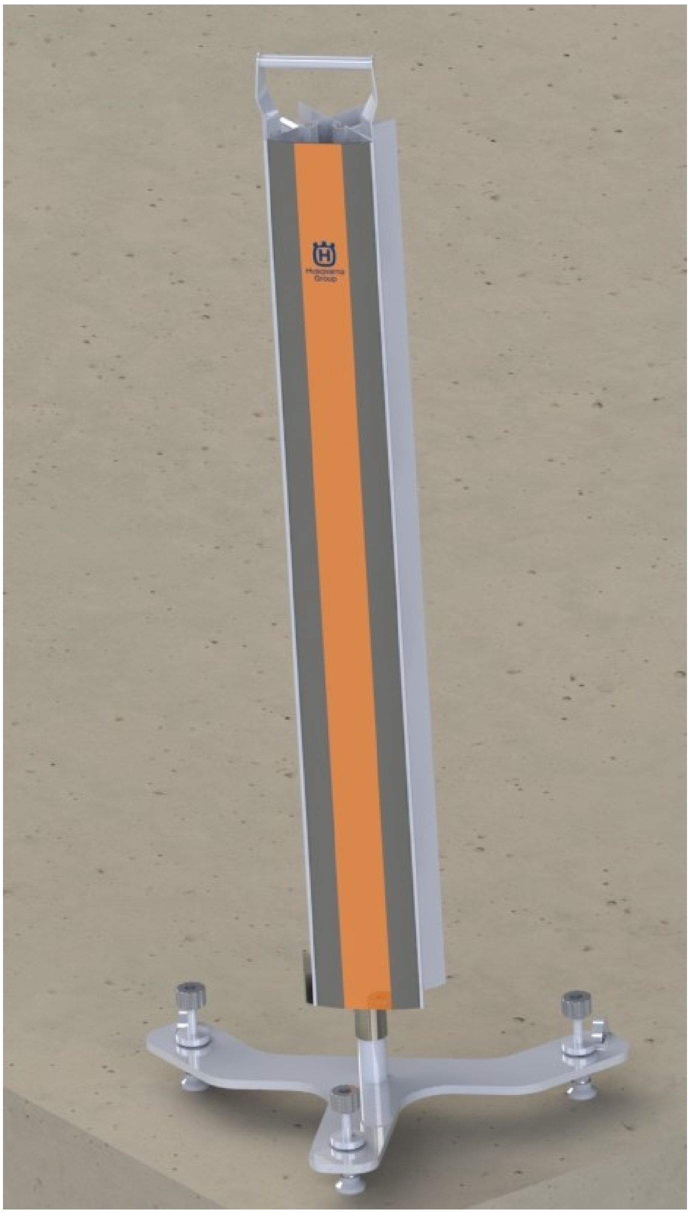

Figure 6.4: Plastic cover for the sending stand

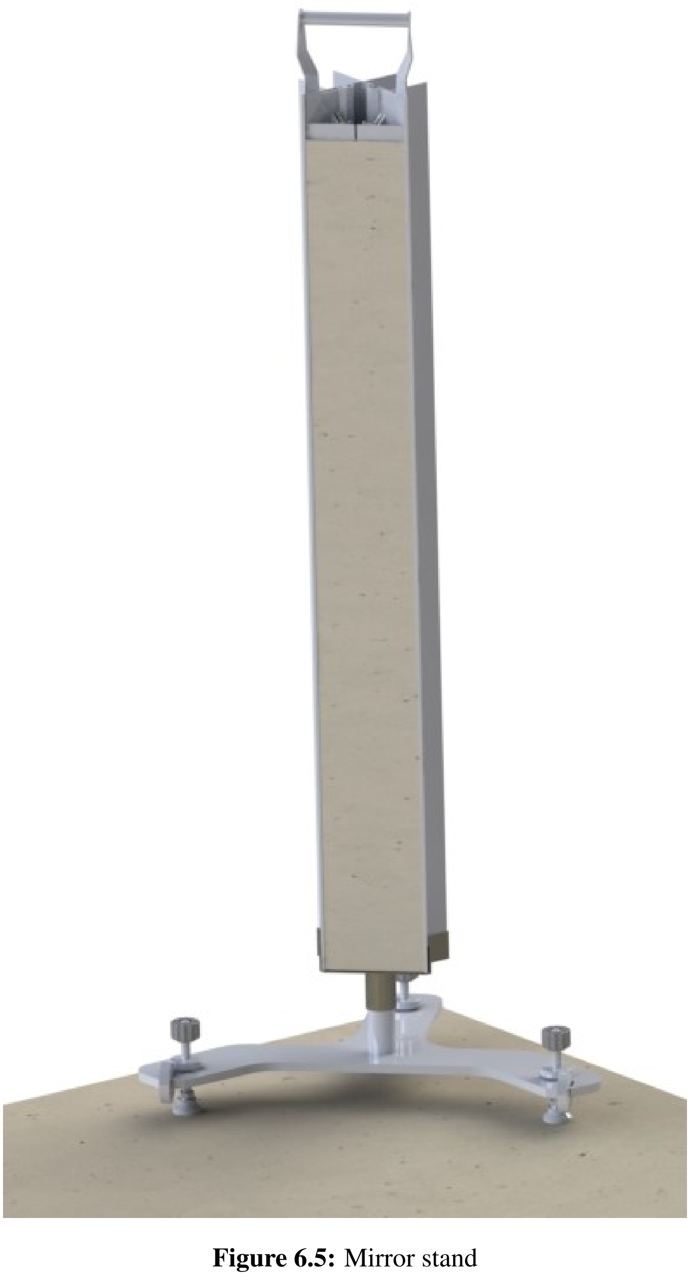

Figure 6.5: Mirror stand

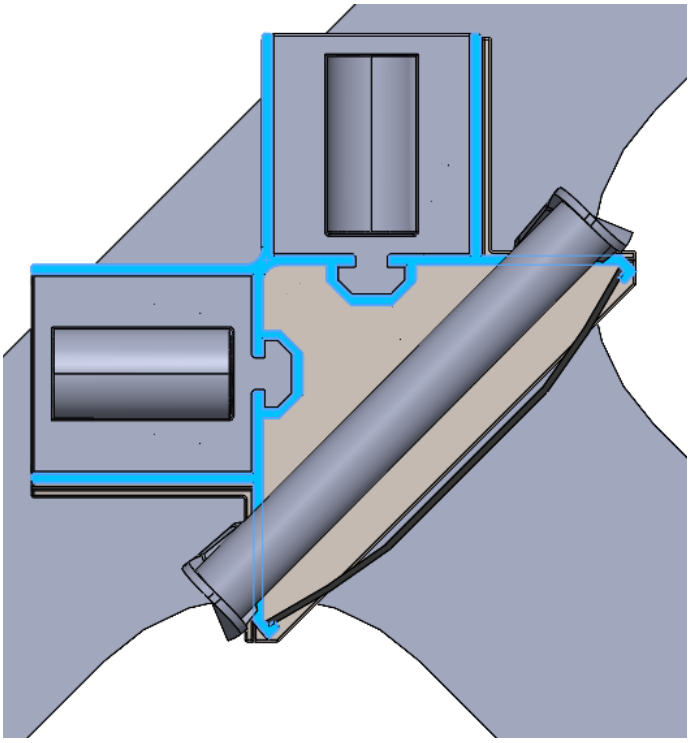

Figure 6.6: Cross section of profile to the modular sending/mirror stands depicted in blue.

Figure 6.7: Handle on top of the sending/mirror stand

6.2.3 Receiving stand

The receiving stand is based upon an U-profile in aluminum into which the receiving light grid can be mounted. The profile can be seen in figure 6.9. The U-profile acts as protection of the light grid as well as the main stabilizing element of the stand. Attached to the top and side of the profile are two handles for transportation and adjustment of the stands. The side handle can be seen in figure 6.10. The profile is connected to the bottom plate by a lockable ball joint which allows the user to control the angle of the profile and the attached light grid. The bottom plate of the receiving stands is smaller than the one in the sending and mirror stands but is otherwise of similar design, except the placement of the wheels at the back of the foot to allow for a slimmer design. The receiving stand can be seen in figure 6.8.

Figure 6.8: Receiving stands

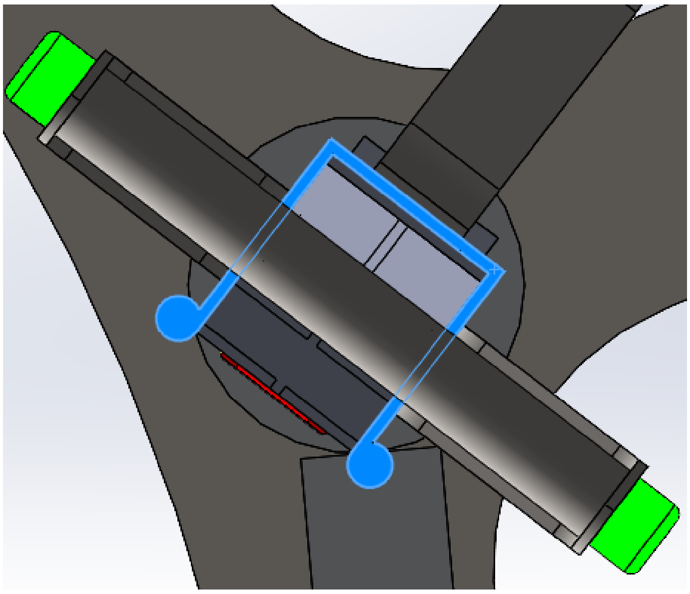

Figure 6.9: Cross section of profile to the receiving stands depicted in blue.

Figure 6.10: Handle on the side of the receiving stand

6.2.4 Feedback system

The feedback system is heavily influenced by the feedback received during the testing of concept Y 2.0, in which the test subjects remarked the necessity of plenty of feedback.

The feedback system includes lasers, targets for lasers and lights indicating the status of the system. The laser can be seen in figure 6.11. The targets for the lasers helps the user find the correct placement and angle to successfully establish a connection between the light grids and can be seen in figure 6.12 and 6.13. This is done by adjusting the receiving stand, using the flexibility of the ball joint, until the laser beam reaches the markings on the back most plate of the laser target. When connection is established the user locks the ball joint in place. This obviously has to be done to both receiving stands. The lamp mounted on the top of the receiving stand marks if connection has been established between the light grids: green if connection is established and red otherwise. The lamp and handle can be seen in figure 6.14.

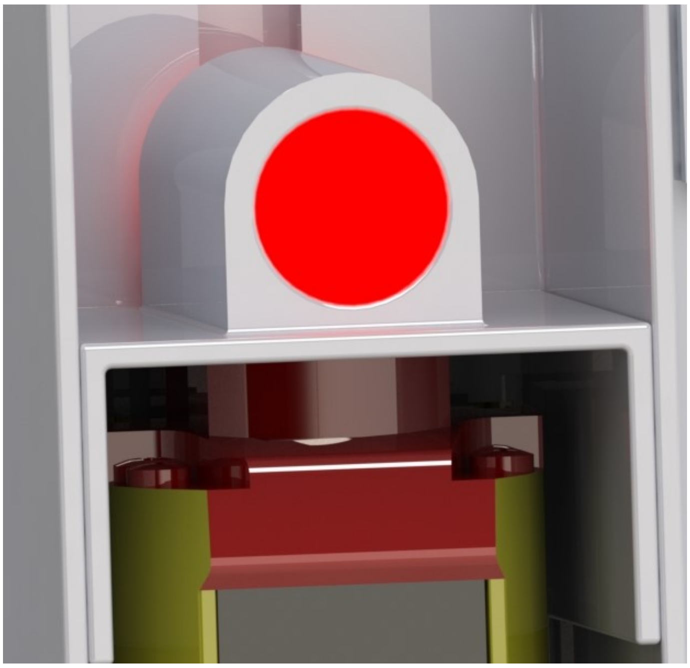

Figure 6.11: Laser mounted above light grid attached to the emitting stand.

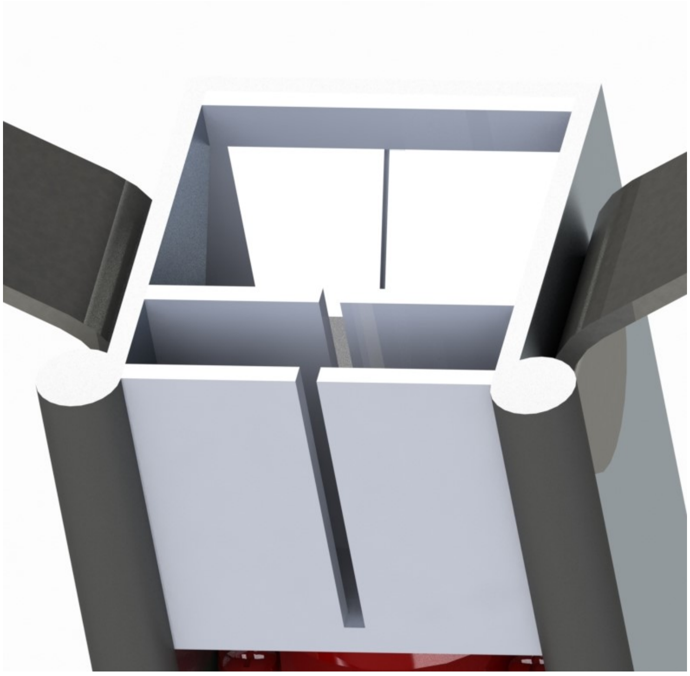

Figure 6.12: Laser target on receiving stands.

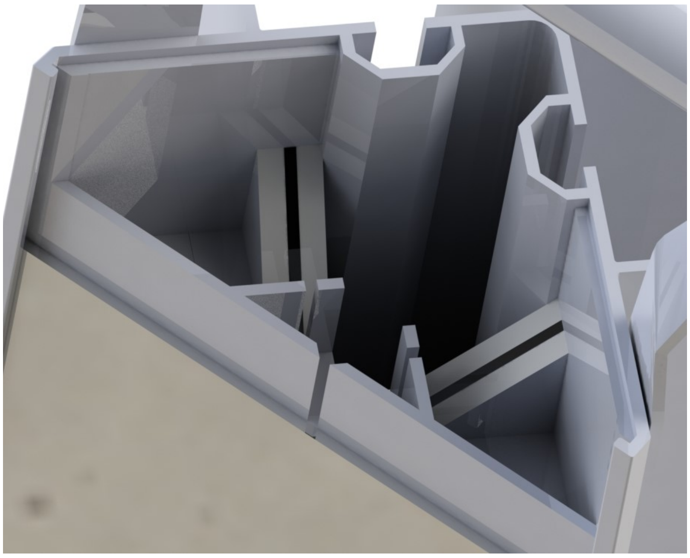

Figure 6.13: Laser target on mirror stands.

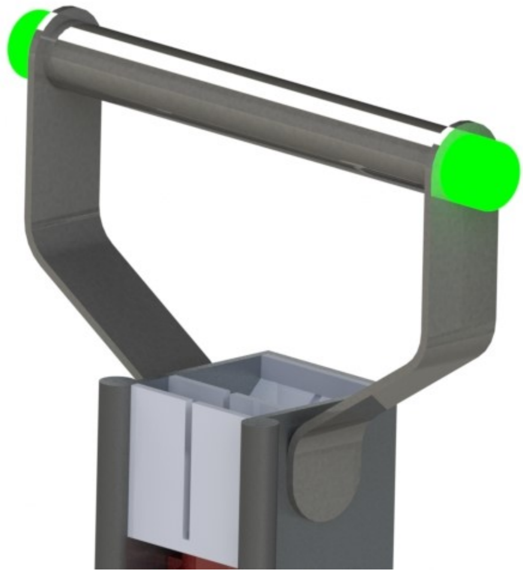

Figure 6.14: Handle with feedback lamp on top of receiving stand.

6.2.5 Design idea behind bottom plates

The two bottom plates are made out of steel and are both designed to occupy as little space as possible while enable placement in corners and providing sufficient stability and support of the stand. As shown in 6.16, these restrictions forces the bottom plate of the receiving stands to be smaller then their counterparts in the mirror and emitting stands. This is possible because of the significantly lower weight of the receiving stands which also contributes to the mobility and thus the usability of the stand. Both bottom plates are equipped with three base screws with which height and angle of the bottom plate can be controlled. The connection between respective profiles and bottom plates are placed in the middle of the plate to make the stands as stable as possible. Since the stands rests upon the three base screws, their placement is ultimately what decides the stability, how easy it is for the stand to fall over, of the stand. As such the screws are placed as far away from the connection point as possible while still allowing the stands to be small enough to fit into corners and not interfering with the path of the grinding machine. Both of the bottom plates are designed with these restrictions in mind, as explained in figure 6.15 and 6.16. The bottom plates can be seen in figure 6.18 and figure 6.17.

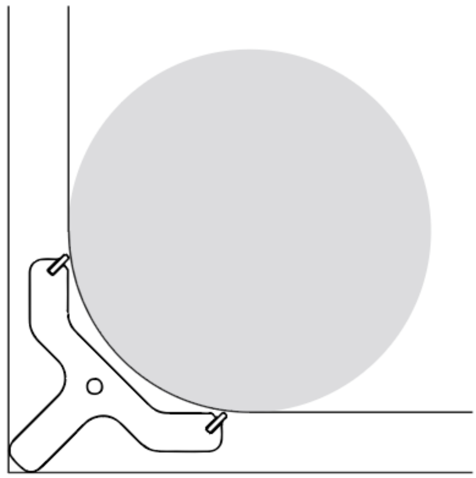

Figure 6.15: Sketch depicting the shape of the bottom plate of the emitting/mirror stands and how it fits into corners while not interfering with the head of the grinding machine depicted in grey. The areas between the lines are the areas not reached by the grinding machine which needs to be processed by a edge grinder later.

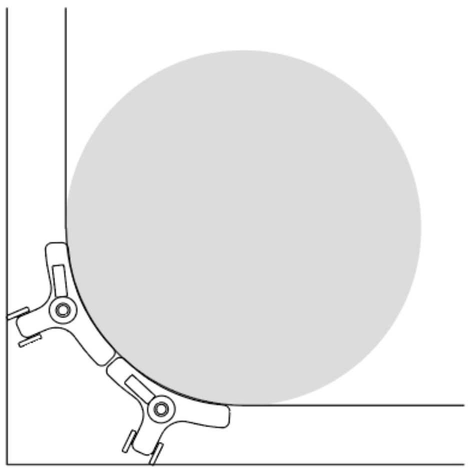

Figure 6.16: Sketch describing the two bottom plates of the receiving stands at a similar placement as the one depicted of the emitting/mirror stands in 6.15. The need for two bottom plates forces each of them to be smaller.

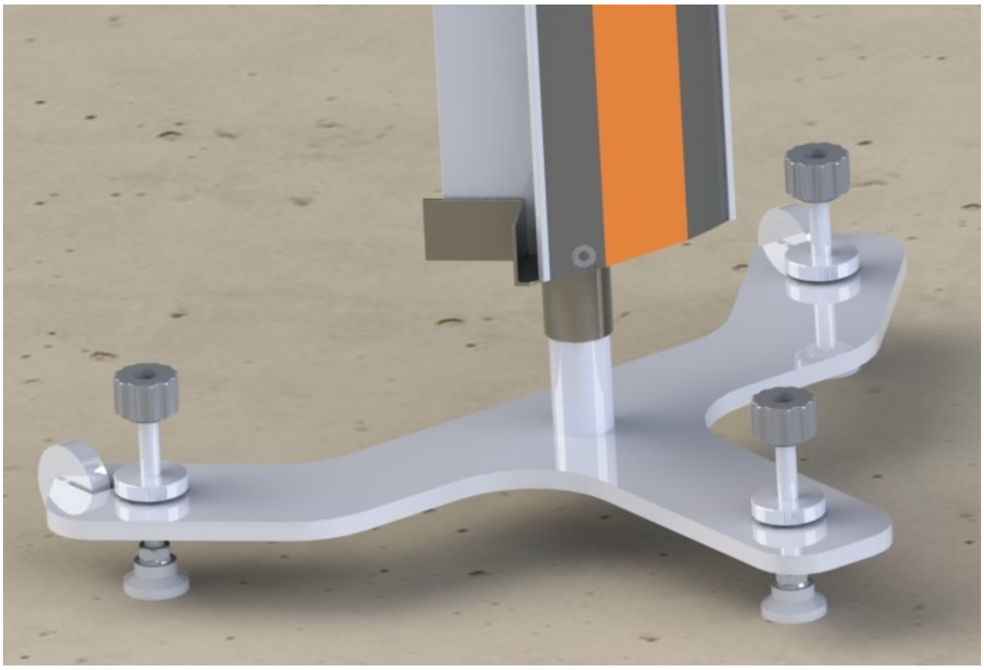

Figure 6.17: Bottom plate of emitting stand.

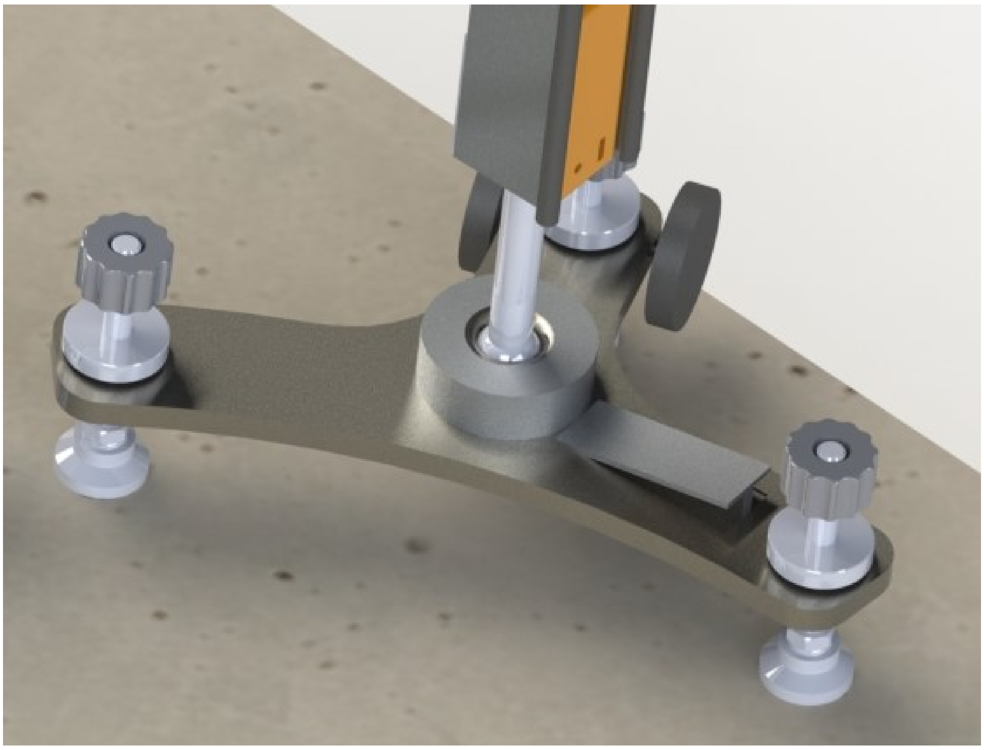

Figure 6.18: The bottom plate of the receiving stand.

6.2.6 Ball joint and pedal

The locking mechanism of the ball consists of a pedal placed on the upper side of bottom plate of the receiving stand and can be seen in figure 6.19. When the pedal is pushed down, by the users foot, the cup around the ball is tightened and the ball is locked in place. When the pedal is pressed upon a second time the ball is freed and the stand may be moved again.

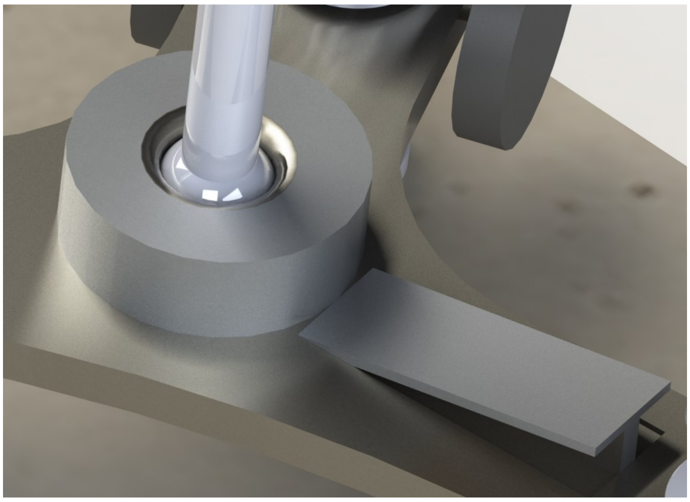

Figure 6.19: Ball joint and pedal.

6.2.7 Compliance with product specifications

The Hydra concept fulfills all of the product specifications, except for specification number 20, in theory but needs to be further evaluated to ensure fulfillment in practice. The compliance with the product specifications are further discussed in chapter 7.5.

6.3 Material selection

The parts of the stand will consist of the materials shown in table 6.1. The material selection is further discussed in chapter 7.3.

Table 6.1: Material selection.

Part	Material
Bottom plate	Structural steel
Profile	Aluminum
Laser holder	Plastic
Cover with Husqvarna logo	Plastic
Laser targets	Plastic
Mirror	Mirror glass
Handle	Structural steel
Ball joint	Structural steel

6.4 Manufacturing

The concept design of the stands has been made with manufacturability aspects taken into account. The goal of the design is a cheap and easily manufactured product. The aluminum profiles are to be produced by extrusion.

6.4.1 Aluminum extrusion

Aluminum extrusion is a method used to transform aluminum alloy into objects with definitive cross-sectional profiles. Aluminum extrusions have many good qualities and are lightweight, strong, and corrosion-resistant, sustainable, etc. Extrusion is a manufacturing method with many advantages. An extruded aluminum profile is easily tailored with a high ability to chose a complex design. The tooling is relatively inexpensive with short lead times which facilitate prototype development and product launch. Another advantage of extrusion is that complex shapes can be made in one seamless piece without mechanical joining. This gives a stronger product compared to a comparable assembly ("Aluminum Extrusions Offer Several Benefits", n.d).

Chapter 7

Discussion

7.1 Future work within the project

The final product is a conceptual system level design and requires extensive future improvements and testing before introduced to the market.

Further testing of the bottom plate to find the ideal weight is important for the final product. The bottom plate needs to be heavy enough to not fall over from wind or a being hit but still be able to be lifted ergonomically. According to Swedish workplace regulations, should lifts over 25 kg not occur regularly in a workplace. If the worker performs multiple lifts a day the weight should not exceed 15 kg. Therefore the maximum weight of the stand including the bottom plate is set to 15 kg ("Manuell hantering", 2020). When the design and material choice of the bottom plate are finalized should tests on both virtual and physical prototypes be performed.

The prototype tests showed that one of the most important and critical aspects of the prototypes are the lasers and laser targets. To be able to connect the emitter and receiver easily a well-functioning laser is essential. To ensure a satisfying final product the precision and performance of the laser used for the final product needs to be evaluated and carefully tested.

In the interviews done during the data gathering process, the experts expressed that one of the most important features to implement in an autonomous solution was the ability to mute the light grid. The user must be able to walk in and out of the work area to inspect the floor and machine without stopping the grinder. The Orion light grid has a built-in muting function that can be used in the system. The muting could be controlled by a small button on the hand-control of the machine, the light grid stand or, the camera stand. A signal to clearly indicate that the security zone is down is to be integrated into the feedback system and be shown with a big red lamp. The details of the muting and how the user is going to control it has not been a part of the project and is to be decided.

The goal of the modular solution is to minimize the tool cost, the cost for each profile, and the inventory (Gadde, & Larsson, 2016). The project is still in an early phase and the expected number of systems sold annually is unclear. Depending on the number of systems sold a modular profile or two separate profiles could be the most cost-effective. A thorough evaluation of the costs needs to be made to evaluate if the savings from a modular solution exceeds the savings from a more material effective design. A full calculation of the whole system to determine the cost per unit for future pricing of the product is also to be made.

A detailed manufacturing plan for the system is to be decided after the design is finalized.

The final product must be able to handle hits, falls, and other impacts. To be able to guarantee this impact tests, both virtual and physical, must be performed. The performance of the aluminum profile must also be evaluated further.

Integration between the stands, the navigation system, and the camera has not been a part of the project.

7.2 Adjustment of ball joint and laser

For the Hydra concept to work properly the feedback system and the mechanisms of the ball joint needs to be correctly installed and configured. If the laser is not correctly aligned to the infra red beams the feedback system will not work as intended which would severely undermine the usability of the system. The same applies to the ball joint and the locking mechanism which needs to have a satisfactory feel to them. If these fail to lock the joint in a satisfactory manner, which includes no slipping or additional flexing of the receiving stand, the user will have to counteract these errors manually, which affects the usability and operator time saved.

7.3 Reasoning behind materials used

Structural steel is chosen as the material to acheive a heavy bottom plate. A heavy bottom plate is required to get a stable stand with a low center of gravity. Structural steel is also chosen for the handles and the ball joint. Aluminum is chosen for the profiles because of its low price, weight and the ability to use extrusion to achieve a complex cross-sectional profile design. The laser holder, laser target, and cover with the Husqvarna logo are made out of plastic. None of the plastic parts are exposed to impacts or forces and therefore are plastic a suitable material.

7.4 Limitations

7.4.1 Relation between the project structure and results

As presented in chapter 4 and shown in figure 7.1 the project is based around first conducting research and then using the information collected in an iterative concept development phase. The results presented in this chapter are heavily influenced by this approach and the time frame of the project. Since no mayor research were done between the iterations of different concepts, no mayor changes in the proposed solutions could take place. If instead the research phase was incorporated into the iterative process, by doing additional research not just into the design of concepts but into how the research questions could be answered, the concepts developed would certainly be different from the one presented here. This method is described by Craig Larman in *Iterative Development: A Manager's Guide* (2004) as Evolutionary iterative development, where the requirements, estimates and solutions all evolve in each iterative cycle. This approach may have been suitable to this project it it were not for the strict time plan imposed.

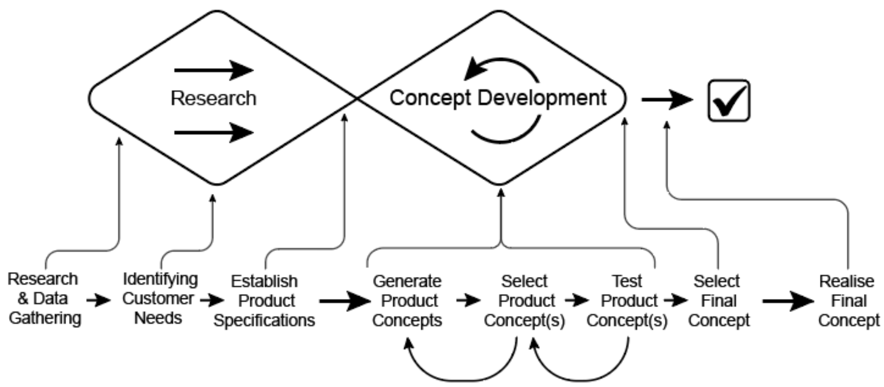

Figure 7.1: Illustration of the project process, presented and described in chapter 4.

7.4.2 Time plan

The original and updated Gantt charts are attached in appendix A. The original goal of the project was a final concept complemented with a FEM-analysis, cost calculation, and plan for manufacturing. The goal of the project was altered along the way because of lack of time and prototyping problems due to Covid-19 to a final conceptual design instead of a final concept ready for manufacturing. The FEM-analysis, cost calculation, and plan for manufacturing were not prioritized and therefore not performed. The iterative development process performed in the project was not part of the original Gantt-chart. More time for prototyping, tests, and adjustments of the concepts was required as a result of the iterative process and added to the updated Gantt chart. The prototypes also required more testing than anticipated.

7.4.3 Physical prototyping

Due to the Covid-19 pandemic the building of much needed physical prototypes were limited. This forced the testing and evaluation of most design concepts to be done theoretically and without any mayor iterations in the few physical prototypes which were built.

7.4.4 Testing

The tests performed on the light grids were done to get a feel of the actual limitations of the equipment in the way they were going to be used. The light grids used during the testing were not the same as the ABB Orion 2 light grids proposed for the final product. This is a major source of error and further testing may need to be done to ensure that the light grids are suitable for the application.

The usability tests of concept Y 2.0 were performed with a physical prototype of the concept. The prototype lacked a functional locking mechanism of the ball joint, wheels and were significantly lighter than the proposed weight. These errors were not deemed serious enough to consider the results of the tests as invalid.

7.5 Compliance with product specifications

The system needs to be built and thoroughly tested before any of the subjective specifications, marked with Subj. in table 7.1, and the specifications addressing accidents can be evaluated. This also includes specifications 5, 6, 13, 14, 18, and 19, marked with stars below, which are not subjective specifications by definition but which are hard to make a correct analysis of without physically building the system first. Specifications 5 and 6 are depending on the final design and material choice which are to be determined. Specifications 13, 15, and 16 are target values set to 0 which makes them hard to evaluate. The goal is to have zero accidents involving humans or surroundings but if technical problems occur is it difficult to guarantee. The specifications with lower importance have not been given as much consideration as the specifications with higher importance. As a result of this specification number 20 has not been fulfilled.

Table 7.1: Table showing the target specifications

No.	Metric	Imp.	Unit	Value
1	Weight	2	kg	15
2	Transportation height	2	cm	100
3	Maximum height	1	cm	130
4	Maximum width	1	cm	40
5	*Unit manufacturing cost, system	2	k SEK	100
6	*Unit manufacturing cost, stand	2	k SEK	1,5
7	Ease of transportation	2	Subj.	
8	Usability	3	Subj.	
9	Grinding area	2	m^2	225
10	Result of grinding	3	Subj.	
11	Possibility to enter	3	Binary	Yes
12	Autonomy	3	Level	4
13	*Errors	2	Number	0
14	*Operator time saved	3	%	70
15	Accidents with users	3	Number	0
16	Accidents with surroundings	3	Number	0
17	*Setup time	3	Min.	15
18	*Impacts to failure	2	Number	200
19	Setups to failure	2	Cycles	2000
20	Pieces for transportation	1	Qty.	1
21	Water resistance	2	IP Code	IP65
22	Tipping point	2	Degrees	25
23	Light disturbance	1	Binary	Pass
24	Maximum distance to wall	3	cm	10

7.6 Responsibility

The operator will have responsibility for the final grinding result. The autonomous solution will free time for the operator on the work site and control the steering of the machine but will not be intelligent and will not be able to make decisions on tooling or other grinding parameters. It is important to mediate the conditions and limitations of the system to the operators to avoid errors and misuse of the system.

The final responsibility for obtaining the safety of the system also lands on the operator. Objects such as loose screws or protruding reinforcements are not detectable for the system. If the work area contains such objects harm can be caused to humans or surroundings. The operator will also have the ultimate responsibility to guarantee a correct setup and configuration of the system.

Chapter 8

Conclusion

This chapter presents the conclusion of the project, answers the research questions and proposed further research.

The Hydra concept is the main result of this project and compromises a full safety system for a mobile robotic cell, tasked with notifying the control system if any unauthorised object enters the zone of operation. The system is successfully designed with usability and cognitive ergonomics in mind.

8.1 Answers to research questions

The project strives to answer following research questions based upon the project idea presented in chapter 1:

- Question 1: Is it feasible to design a safety system which fulfills the needs of the system while maintaining a high degree of usability?
- Question 2: Is there a market segment for this product?
- Question 3: What are the main parameters affecting the system and how it is set up?

Question 1

The results from the project clearly indicates that it is feasible to design a safety system which in a satisfactory manner fulfills the needs of the system as well as achieving a high degree of usability. Exactly how the system will be designed and the actual operator time saved will be determined by Husqvarna in later stages of the project.

Question 2

The interviews with market experts proved that there is a clear market segment for this kind of system and its uses. The consensus was that customers interested in an autonomous grinding system would be companies with an already established interest or use of the latest technological solutions as well as being eager to make their operation more efficient. Companies that show these characteristics are usually medium to large sized companies with experience in the industry.

Question 3

As shown by the test results in table 8.1 the α and β angles, shown in figure 8.1, of the light grid are the most sensitive.

The performance and accuracy of the laser and laser targets are also important parameters for the setup of the system. A small angle error of the laser aggravates the configuration and lower the usability drastically. The same applies to the ball joint and the locking mechanism. If these fail to lock the joint in a satisfactory manner, which includes no slipping or additional flexing of the receiving stand, the user will have to counteract these errors manually, which affects the usability and operator time saved.

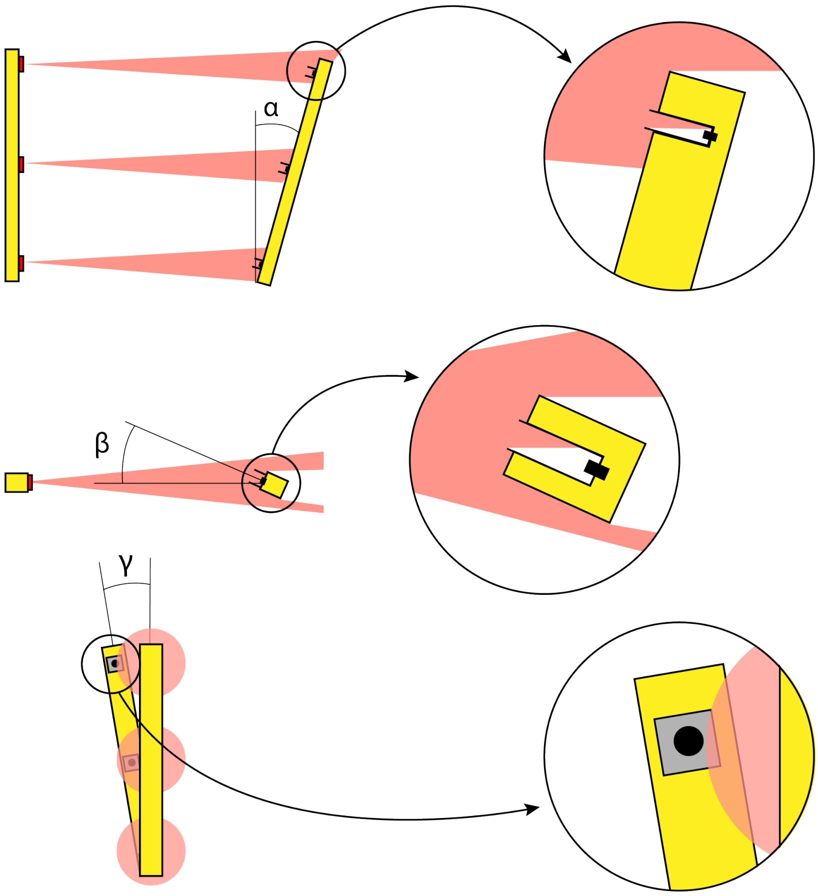

Figure 8.1: Simplified explanation of which angles must be taken into consideration and why when installing a light grid. If the infrared beams are unable to reach all of the photoelectric sensors on the receiver the light curtain is not properly installed. α, β and γ represent the maximal angle for successful installation in each dimension

Table 8.1: Results of tests

Dimension	Measured value	Comment
Length	15 m	Distance where successful installation is easily achieved
Height	136 mm	Maximum difference in height allowed by the testing equipment
α	0.4°	2.9° at a distance of 1 m
β	0.55°	
γ	8.8°	

8.2 Future research

The findings presented in this project clearly indicates the need for subsequent research into the areas in which this technology may be applied and how the mobile robotic cell system may be expanded and improved upon.

As described in 7.6 the operator still oversees the grinding machine and has full responsibility of the actual result of the grinding operation. If the system could be expanded or improved upon to be able to intelligently oversee the result of the grinding this would lead to a significant improvement in the effectiveness of the system. This is a tall task however and would likely include far more advanced autonomy of the system. If level 5 autonomy was achieved, the system would not need any safety equipment and the Hydra system would be rendered obsolete.

The Hydra system could certainly find other uses then the one proposed here. Movable robotic cell could be used as a highly flexible safety system in traditional manufacturing lines, for instance if a manufacturer needs to quickly change how or where the line should operate. Alternative uses of the system also lie in other autonomous tooling or construction applications where there is a need to keep unauthorized objects out of the zone of operation.

Chapter 9

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Appendix A

Gantt charts

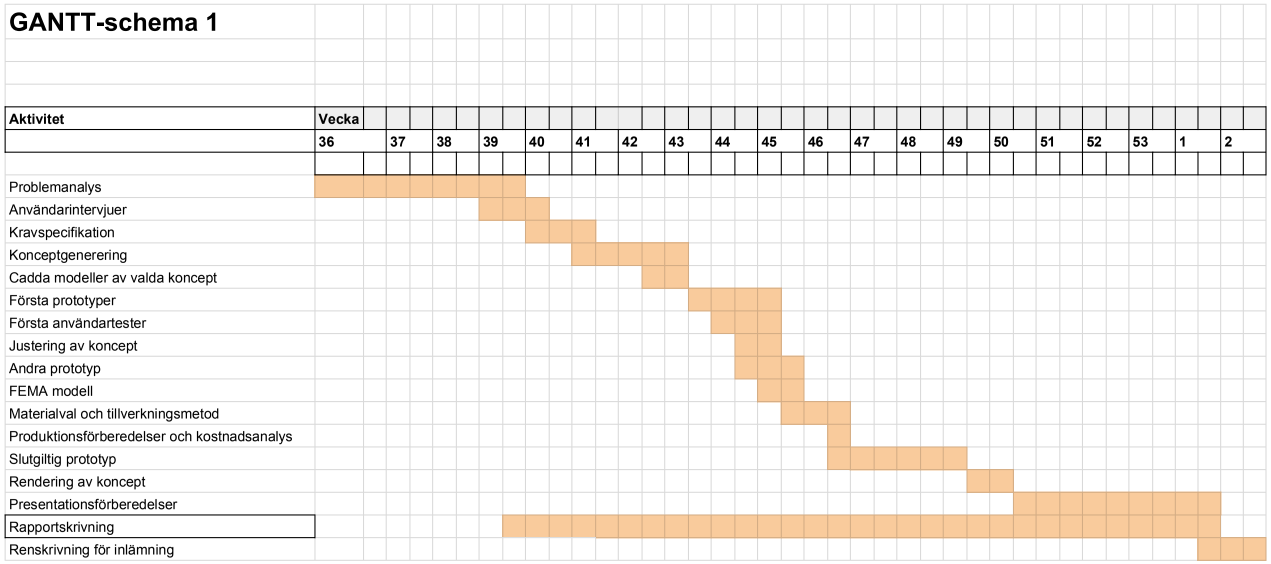


Figure A.1: Gantt chart for original time plan.

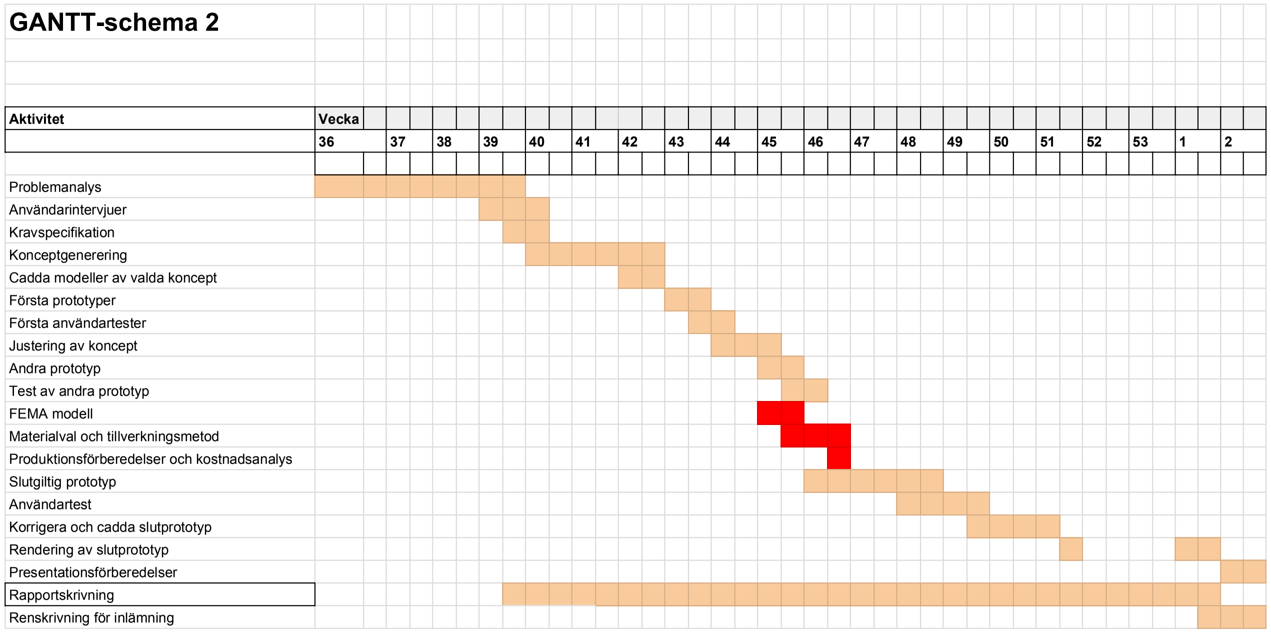


Figure A.2: Gantt chart for project

Appendix B

Interview questions

B.1 Questions

Intro

Examensarbete inom produktutveckling och användarvänlighet.

Projekt om autonom golvslip.

Är det okej att vi spelar in det här samtalet för att kunna lyssna på det senare?

Warm-up

Vad heter du?

Vad jobbar du med?

Hur länge har du jobbat med det?

Vad gör du en vanlig arbetsdag?

Main session

Frågor om HTCs kunder:

Vad för slags jobb använder kunder HTCs maskiner till idag? Vad innebär ett normalt jobb?

Normalstorlek på slipyta? När sker transport? Tid på samma plats? etc

Är den vanliga kunden specialiserad på slipning eller gör de annat också?

Hur vanligt är det att kunderna utbildar sina maskinoperatörer? Med ex HTC Akademin.

Tror du kunder föredrar “enkla” system som inte kräver utbildningskurs eller utbildar de hellre sin personal för att vara på den säkra sidan? Utveckla gärna.

Hur viktigt är det för kunderna att utrustningen är enkel att packa ihop för transport och förvaring?

När kunden slipar, hur bearbetas kanter och svåråtkomliga ställen?

Frågor om autonoma system

Vad ser du som den största fördelen med ett självkörande slipsystem?

Vad tror du är det viktigaste för kunden när man köper in ett sånt här system? (Säkerhet, användarvänlighet, ergonomi, funktion, pris)

Hur tror du kunder ser på säkerheten kring självkörande slipmaskiner?

Hur lång tid får det maximalt ta att sätta upp ett självkörande slipsystem?

Ser du något som talar emot att kunder skulle vara intresserade av ett sånt här system? I sådana fall varför?

Cool-off

Har du några andra tankar eller någonting du vill tillägga?

Close off

Tack för oss!

Appendix C

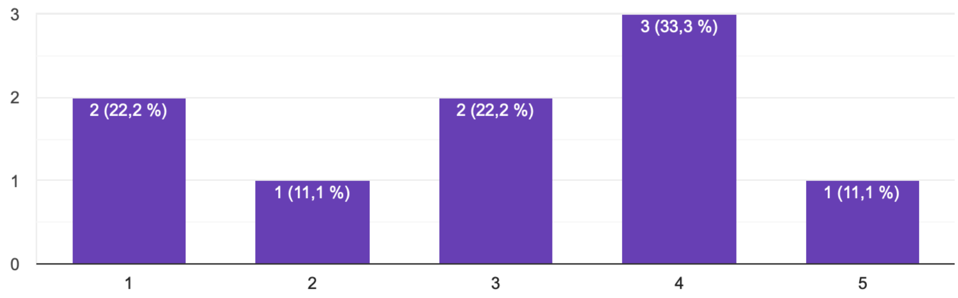
User test

C.1 Questions and answers

Vad tyckte du var svårast med testet?

- Mer feedback på prototypen
- Svårast att få sista ridån i kontakt
- Svårt att veta vart mittpunkten på lasern är
- Ridåerna väldigt känsliga. Många felkällor
- Visste inte vad som skulle ändras när siktet var på rätt plats men ingen kontakt. Vilken parameter ska ändras.
- Att förflytta den på golvet. Hjul under?

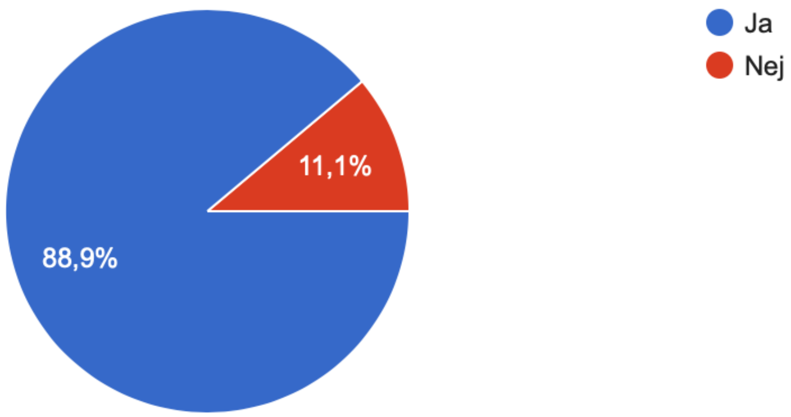
Hur svårt tyckte du att det var att få kontakt mellan stativen? (1-5)



Vad tyckte du bäst om med prototypen

- Siktet på spegeln och handtaget
- Lätt koncept i teorin, överskådeligt
- Lätt att flytta för att anpassa området

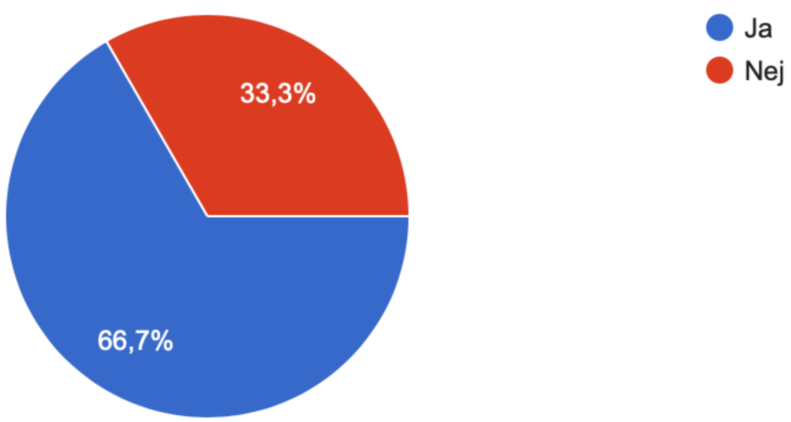
Vad skulle du vilja ändra med prototypen, något som kändes svåranvänt, krångligt eller liknande.



- En smalare och skarpare laser
- Göra det mer idiotsäkert

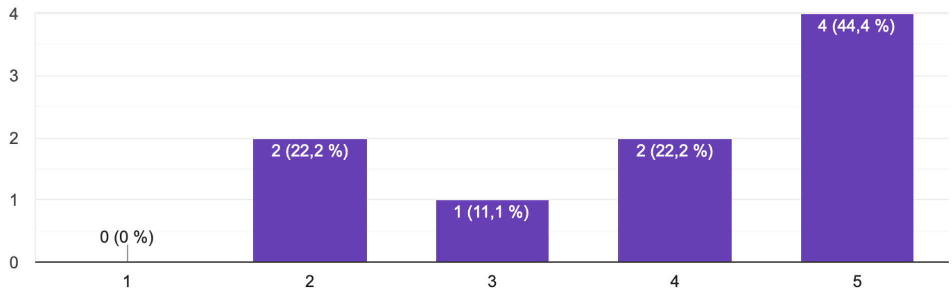
- Mer feedback vid inställning
- Ha ett mer öppet sikte på handtaget för att veta hur man ligger till och hur man ska förflytta den

Var det något du saknade hos prototypen eller hela systemet?



- Mer precision i laser och sikte
- Mindre komplexitet
- Något som gör att man ser lasern även utan vägg bakom
- Mer feedback

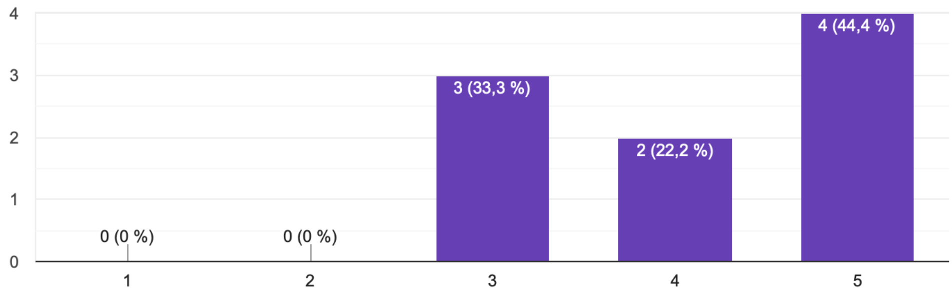
Hur lättanvänd tyckte du att kulan var vid injustering? (1-5)



Övrig feedback på kulan

- Mer friktion
- Möjlighet att låsa i olika leder

Hur lätt tyckte du att prototypen var att förflytta?



Vad tyckte du om lasern och de olika lasersikterna?

- Mer skarp och fokuserad laser
- Överlag positiva till iden
- Lite för stort korrekt område på spegelsiktet

Övrig feedback

- Bra handtag, med en trögare kula skulle det kanske vara bra med tvåhandshandtag

- Vore bra med mer instruktioner i form av symboler, färger och former för att lättare förstå