Robotics
Robotic Manipulators P2

2. Semester project - Spring 2016

AALBORG UNIVERSITY
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Sub-theme:
Project proposal nr. 2: UR-robot in production set-up

Project Period:
P2, Spring 2016
Date: 01/02/2016 - 24/05/2016

Group number:
B128

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Pages: 97

2nd semester
The technical scientific faculty

Abstract:

This project revolves around industrial manipulators in a production setup, with reducing the repetitive work done by the operator as the initial problem. The case being used is a work station located at Grundfoss in Bjerringbro. This is done by implementing a viable robotic solution, that can overtake the repetitive tasks, while not hindering the current production. This entails analyzing the work station, researching a suitable industrial manipulator, CAD modeling, kinematics, risk assessment, testing, and more. The industrial manipulator which the project ended up using is a UR5 from Universal Robots. The final solution is able to replace a large part of the repetitive tasks needed done by the operator, but can not do the quality controls needed.

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1 Foreword

This report is written by the project-group B128 in the Bachelor education of Robotics (2. semester) at Aalborg University in the period from 01/02/2016 to 24/05/2016. The main theme is “Manipulators in form of industrial robots” and the chosen sub-theme is “URs in production set-up”. The project centers around a work station located at Grundfos in Bjerringbro, which is being used as the case for this project. This entails programming and simulations of manipulators as well as calculations on the kinematics of the manipulator. When referring to sources in this report, end-notes are used and the references are placed after the claims or in the beginning of a section. All figures are refered to their origin, unless they are made by the group.

Appreciation and thankfulness goes to the people who have helped with the guidance and answering our questions: to the other Robotics students from our semester, to the two project supervisors - Jan Dimon Bendtsen and Mette Mosgaard and at last but not least, to Michael Røddik and Jan Folsack from Grundfos for being available to lend a helping hand.

2 Introduction

Most large-scale production companies have at least some robotic solution in their production line, not only doing the heavy lifting, but in a still higher degree, repetitive assembly of a variety of products. One of these companies are Grundfos, a world-leading pump manufacturer, who has an almost fully automated production line.[1]

Even though robots have been present at factories for over a hundred years, it is not until recently that these manipulators have been developed to cooperate with humans. In this project the goal is, in collaboration with Grundfos, to create a viable solution for a given work station, where a human is present.

When introduced to the work station at Grundfos, it was clear that this particular station included a lot of repetitive work, which potentially could lead to severe injuries. This is desirable to reduce for Grundfos, whom took contact to the group through an intermediary. This solution to be developed, will have to contain a manipulator, safe enough for a worker to maneuver around.

Therefore an initial problem statement, was crafted. From this statement, an analysis of how severe the problem with repetitive work is made. Then an analysis of how humans interact with robots and the ethical and societal impacts of replacing a human worker with a manipulator is conducted. Lastly the given work station is analyzed. All of this leads up to a set of requirements.

With the requirements done it is possible to go into the solution for this product. A lot of different parts will go into the solution. First of, kinematic models for the UR5 were made, a gripper that suits the specifications needed for the project was also made and printed, simulations will also be made and live tests in the lab to test both simulations, kinematic models, the gripper and acceptance tests that were set up in the requirement specification. Having these elements, it can then be concluded upon whether the solution is a success or not.

2.1 Initial Problem Statement

How can we reduce the repetitive physical labor in a flexible work environment?

3 Case Description

This chapter a describes of Grundfos and some of their key values are presented. This gives the reader a short description of Grundfos and their current state. It covers current products, economics, history and values. This insight into the world of manipulators is the foundation for future research.

3.1 Grundfos

Grundfos is primarily a pump manufacturer. It is the worlds biggest pump manufacturer with subsidiaries around the world, with their biggest complex in Bjerringbro, Denmark. Worldwide Grundfos have more than 18800 employees as of 2014, with an annual revenue of 23.6 billion DKK, and are represented with more than 80 corporations in 55 countries[2].

The following part about the history of Grundfos is taken from the same source[1].Poul Due Jensen founded Grundfos in 1944, which was named Bjerringbro Die-casting Foundry and Machine Factory and would first later become known under the name of Grundfos. In 1945 the company began developing their first pump due to an order of an automatic pump, the pump was finished in 1946 and was named Foss 1. In the next couple of years they continued to develop and sell pumps and in 1949 they exported their first pump to Norway. Grundfos began expanding outside of Denmark in 1960 and started a subsidiary in Germany. Nine years later in 1969 Grundfos started to develop their own production machines for the circulator pumps, which lead to a lot of time being saved in the process. In 1977 Poul Due Jensen passed away and his son Niels Due Jensen took over as CEO, A couple of years later in 1980 they started to focus on energy savings and that would become an important focus later on, when one of their values would become sustainability. In 1989 Grundfos started to automate their production with industrial manipulators, over the next several years Grundfos would continue to expand their use of manipulators and today they have well over 200 robots making it heavily automated. Today Grundfos has a new CEO, Mads Nipper who took over in 2014

3.1.1 Grundfos Values

Grundfos as a company has six main values: sustainability, open and trustworthy, people in focus, independent, partnership and to be ambitious.[3]

The first of their six core values is sustainability, which refers to responsibility while still being competitive. And trying to leave less of an environmental footprint, meaning products that reduce climate impact and use less nature resources. And as one of the focuses at their training program give future employees the mindset to think sustainability.[3]

The second value, open and trustworthy, referring to being open with employees and getting a mutual trust. This mentality is used in other aspects such as negotiating with partners. And they strive to be as transparent as possible.[3]

The third value, which is people in focus. This means that Grundfos is a workplace where everyone has opportunities for influence and it is the people working at Grundfos that makes the place. Another important part of the value is that everyone should feel respected and appreciated.[3]

The fourth value, be independent, is all about the company having a healthy economy. This is accomplished through the Poul Due Jensen foundation which was created in 1975, the foundation is the majority shareholder and is used for new investments and growth. Grundfos says that surplus is a means to growth.[3]

The fifth value, partnership, is about how Grundfos strives to create value through relations with costumers and suppliers, leading for growth.[3]

The last value is to be ambitious, for Grundfos, this means to challenge themselves to create the best possible solution while still keeping the best possible quality. [3] Sustainability in any form is important for Grundfos, which is why it is important to have the required knowledge about the different kinds of sustainability, and that it is considered and present in this project. Sustainability can be categorized in three different parts and those are social, environmental and economic. So when Grundfos declares that employees well being means a lot to them it is part of a social sustainability.

3.1.2 Automation of Grundfos

Today Grundfos is heavily automated, but they have not experienced a big decline in employees, but rather managed to uphold almost the same number of employees[4], which is not consistent with the paper The Future Employment Impacts of Industrial Robots written by David R. Howell that shows that "the ratio of job displacement to job creation is quite large"[5]. So even though it can be seen in figure 3.1 that they have had an increase of robots at Grundfos, with 172 robots in 2007 and well over 200 robots in 2014, it is quite remarkable that they have not experienced a significant decline of employees, in fact they increased their number of employees from 2013 to 2014[4], while in the previous years they have also had a constant increase of manipulators. In fact in 2001 Grundfos had 10985 employees[6] compared to the 18878 in 2014[4]. Though on the other hand an answer to this development could be that because of the automation they have been able to increase productivity and therefore the yearly turnover would have naturally increased too, which is supported by looking at the turnover in 2001 which was 10.214 million DKK[6] while in 2014 the turnover in 2014 was 23.618 DKK[4]. Because of that increase in revenue they could have expanded their business and that might account for the increase of employees at Grundfos. That development shows that automating can lead to an increase in employees, although not directly but for an increased revenue due to expanded production.

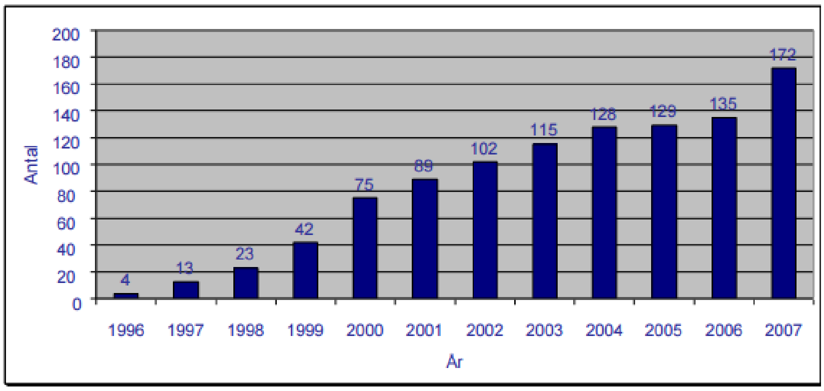

Figure 3.1: Evolution of robots at Grundfos [7]

Grundfus value sustainability in their business to be able to uphold quality, have a good

relationship with their employees and still make valuable solutions for work. Grundfos value their employees and because of that, they try to have the best working environment. The next chapter deals with working environment this project will try to reach.
Some of the project requirements are: "To investigate the use of flexible robot setups based on manipulators from Universal Robots, reduce production costs and improve on the working environment". The project uses a workstation located at Grundfos as a study case to meet these requirements. The work station is currently manually operated by one person and described below in figure 3.2.

3.2 Use case scenario

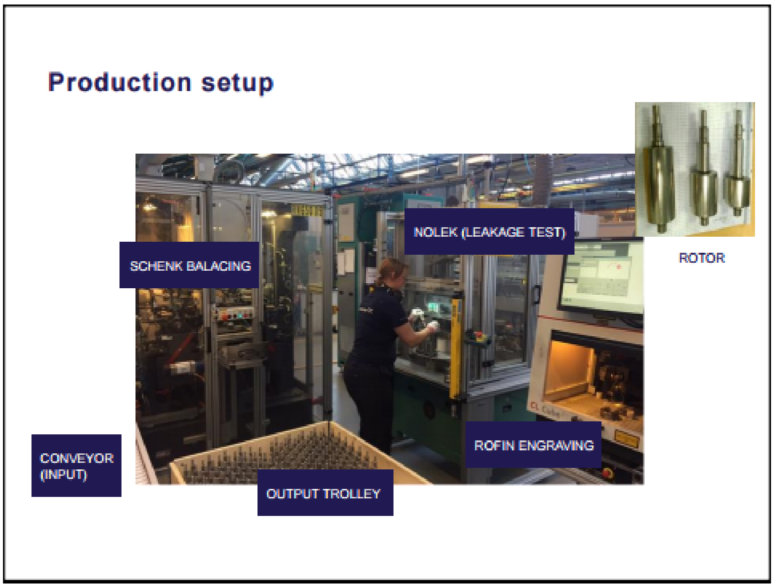

Figure 3.2: The workstation [7]

Case Work station at Grundfos

Description Rotors are manually collected from an incoming conveyor, while visually checked for welding defects, and placed in a Schenk balancing machine. Thereafter the rotors are placed from the Schenk drawer in to a Nolek leakage test machine, while visually checking for burr and mark defects. After this the Rotors are engraved. Lastly the rotor is placed on a pallet.

Assumptions A full pallet is replaced by a empty by the operator. Defect rotors are removed and placed on a separate pallet for later inspection.

Actors Conveyor belt, Schenk de-balancing station, leakage test station, engraving station, pallet one, pallet two, and an operator.

The steps for the entire process is as following.

1. The rotor is collected from a conveyor belt, visually quality controlled for welding defects, and placed in the Schenk de-balancing station. Figure 3.3 is showing the conveyor belt feeding the work station with rotors and the Schenk balancing machine with the drawer closed.

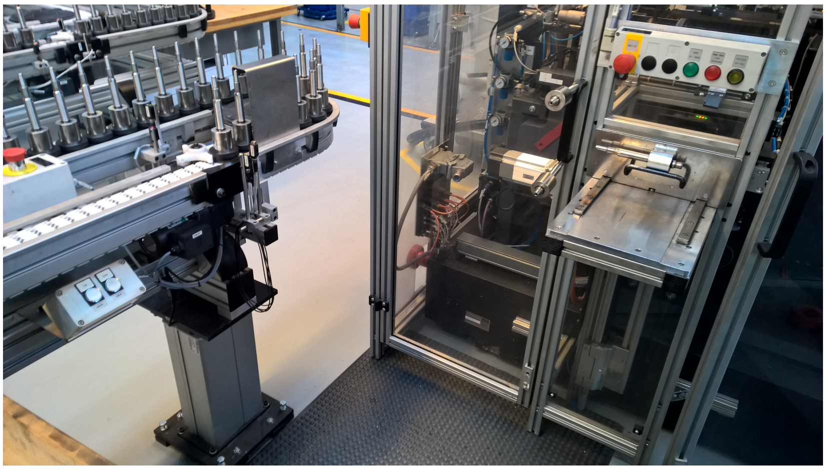

Figure 3.3: Conveyor belt and Schenk

2. The Schenk is started by the operator, this is where the rotors are being balanced. And figure 3.4 shows the open schenk drawer with a correctly placed rotor.

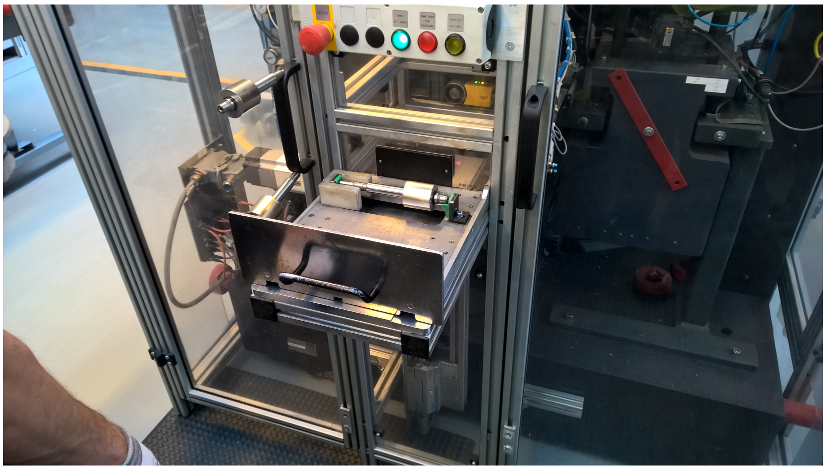

Figure 3.4: Open schenk drawer with a correctly placed rotor

3. When finished the rotor is collected by the operator from the Schenk de-balancing station, visually controlled for drilling and markings defects, and placed in leakage test station.

4. The Nolek is started by the operator. The Nolek leakage testing station holding two rotors and test whether or not there are any faults in the rotors. And can be seen in figure 3.5.

Figure 3.5: Nolek leakage test station

5. The rotor is moved to the engraving station by the operator, here Grundfos engraves the serial numbers to keep track of the rotors. Figure 3.6 shows a rotor mounted in the

engraving station.

Figure 3.6: Engraving station

6. The engraving is activated by the operator.

7. The rotors engravings are controlled and then placed on pallet one by the operator.

The finished balanced and engraved rotors are placed on two different pallets, depending on whether the rotors have defects or not.

The rotors as mentioned before are submitted to several visually quality tests during the process by the operator. The first test is checking for welding defects before placing the rotor in the Schenk drawer. The second is looking for unwanted burrs and marks, between the Schenk and leakage test. The last test is checking if the engravings are placed correctly.

The cycle times of each station are as following: Schenk balancing takes about from minimum 8 seconds and maximal 15 seconds. The Nolek uses an average of 10 seconds to control two rotors for leakage. Engraving takes on average of 10 seconds. The Nolek and Engraving times are set to 12 seconds to keep the flow of production.

The industrial manipulator will need to know the exact measurements for every station of the work station, and the exact dimensions and weight for the rotors.

The workstation contains three stations, the schenk balancing, the Nolek Leakage test, and the Rofing engraving station. The general purpose is to perform quality testing and finishing touches, on the rotor. Part of working within the workstation, includes hard labor and repetitive work, the goal of this project as seen in the initial problem statement is to reduce this. The next chapter will focus on analyzing repetitive work and the possibilities to remove it.

4 Repetitive Work

The purpose of this project is to reduce the repetitive work within a specific workstation. It is important then to show if there is a problem with repetitive work, and the possible risks involved with it.

Repetitive work is defined as any form of work that is characterized by repetition[8]. This could be movement of an object from a factory line, or using a mouse with the computer through most of the day. This has proven to have complications for the workers in the long term. A study done by the Scandinavian Journal of Work, Environment and Health compared the work related damages, between certain factory workers, where there is a lot of repetitive motions, and shop assistant, and concluded that there were a much higher frequency of injuries to the upper extremities like neck and lower back in the factory worker[9]. They also reported that the speed the repetition was done by had an influence in the risk of injury.

Another study by the American journal of industrial medicine (1999) concluded that there is a link between repetitive work and upper-limb muscoloskeletal disorders, such as Carpal tunnel syndrome[10].

These studies illustrate that when repetitive work is prevalent within the everyday work effort, the risks of contracting injuries are increased. They also illustrate that the intensity meaning the speed and force needed to do the work enhances these risks.

This indicates that repeated incidences of repetitive work has certain health consequences for workers. It is not as high of a risk if done in short timeframes but in the long term can have health consequences.

The Danish authority on work environment(Arbejdstilsynet) made an executive order in 2002 on what repetitive work is and how to minimize the risks involved with it. This also entails evaluating when a workstation is repetitive work and how to setup the necessary precautions.[11] The rest of this part is from the aforementioned guide. [11].

In the order, repetitive work is defined, as when similar work motion is repeated with high frequency for a large portion of the day. It is not defined as repetitive work when it is a small portion of the day, meaning if it only consist of less than 10 pct of the average work day.

They define the time of repetitive work by two methods, cycle time and observation time. Cycle time is the time between one subject being handled and another. This is often used within factory work. Observation time is the time a worker spends observing a work operation during the work day. This is mostly used within service and administration jobs.

There are enhancing factors that increase the health hazard of repetitive work. This involves the necessary force to use tools. This could also involve high level of concentration, when a company needs to evaluate the repetitive work of a workstation, the proportion of the workday the repeated motions is done, and the cycle time/observation time. Along with that the enhancing factors can increase the level of repetitive work. The repetitive work will then be defined as being either high-repetitive or low-repetitive.

• High repetitive: is when the cycle time is less than 30 seconds, or if repeated motions comprise more than 50 pct. of the work cycle time. High repetitive work is considered a health hazard for the worker.

• Low repetitive: is when the cycle time is between 30 seconds to 5 min, or if repeated motions comprise between 10-50 pct. Low repetitive is only considered as health hazardous if there are enhancing factors.

If a workstation is evaluated as high repetitive, a plan must be made to reduce it. This could be to increase the number of breaks or have rotation of workers, in the short term. In the long term, automation of the work could be a method of reducing or eliminating the repetitive work.

This indicates a specific definition of a repetitive work. When creating a workstation it is necessary by law in Denmark to evaluate the repetitive and to what degree precautions have to be implemented.

In the annual statement made by Arbejdstilsynet, about the reported occupational diseases shown below, the amount of reported incidences of muscoloskeletal disorders and that it is a high amount of reported incidents can be seen.

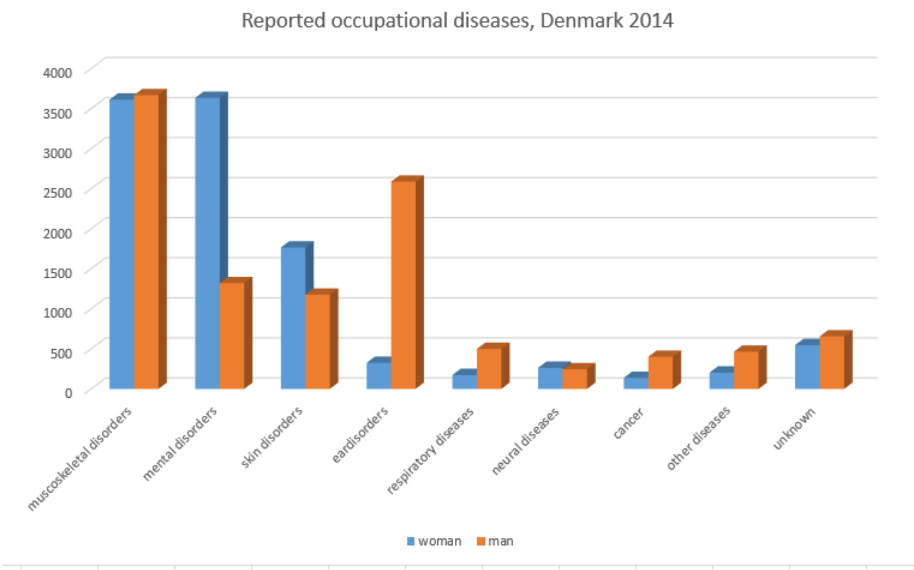

Figure 4.1: Reported occupational diseases 2014 [12]

This indicates that this is an issue that impacts thousands of people yearly. This shows that this is something that must be taken seriously since it has severe consequences for the affected people.

It also illustrates a need for diminishing the repetitive work since it has shown to be a problem affecting many people in Denmark to this day.

Repetitive work has shown, in the long term, to lead to damage of the upper limbs in a way that if repeatedly exposed to it, there is a risk of health consequences.

This could be in the form of upper-limb muscoloskeletal disorders such as carpal tunnel syndrome. When it is needed to define whether or not the repetitive work have been diminished or eliminated, the definition of the repetitiveness of the work can be found within the order made by Arbejdstilsynet. They define it as high repetitive if the cycle time is less than 30 seconds or if the proportion of repeated motion comprise 50 pct or more of the work cycle time. This was the parameters used to measure if the solution will reduce the repetitive work or eliminate it completely.

As part of reducing repetitive work, automation of a workstation is suggested. This is done by implementing manipulators, which have the consequence of replacing certain peoples job negatively impacting their life quality. Therefore in the following chapter, this topic is researched to find out the scope and consequences of this.

5 Robots Replacing Humans

The rapid advancements and the greater degree of diversity within most areas of the robotic field, means machines are able to operate in a still greater degree of different assignments and thereby they are able to do a larger variety of automating manual labor. To clarify to what extent robots are replacing humans, this chapter makes use of different statistics.

The first statistic is the sale of industrial manipulators worldwide, these supply data were collected by the International Federation of Robotics[13]. By looking at figure 5.1 and comparing 2000 to 2014 there is a significant growth in the supply of industrial manipulators. In the period from 2010-2014 the rise were a 48 %. The forecast stipulates that the sales numbers of industrial manipulators will continue to rise in the future. From 2014 to 2018* the forecast predicts nearly twice as many industrial manipulators is manufactured and comparing 2002 to 2018 shows triple amount of industrial manipulators within this era. The main buyers of industrial manipulators are; China, Japan, The US, the Republic of Korea, and Germany with more than 70 % of the total sales going to these countries. Although these numbers only represent the sales of industrial manipulators, they leave a clear impression of the escalating usages of automation.[13]

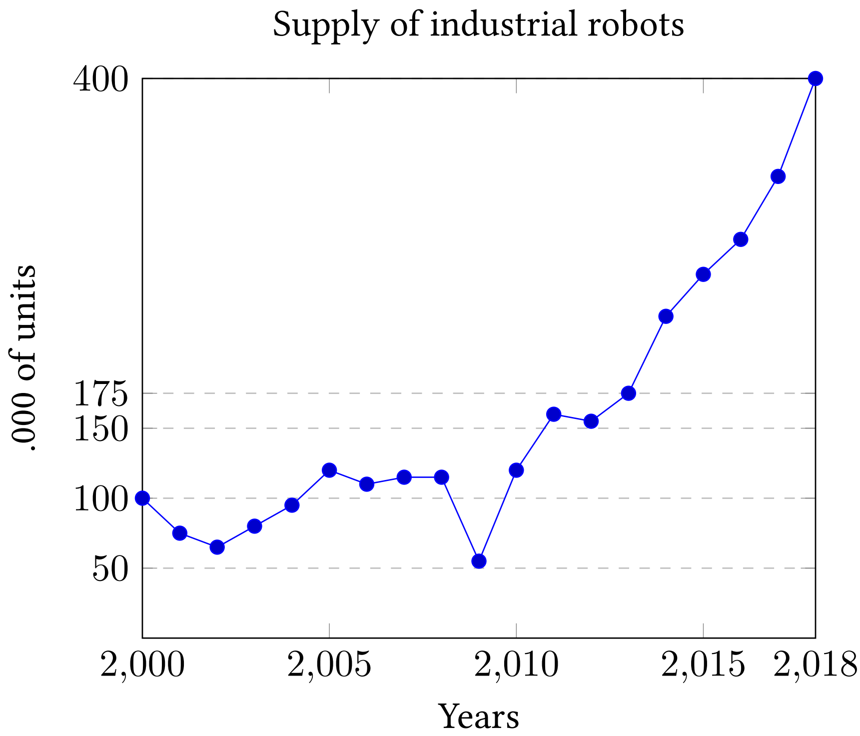

Figure 5.1: Worldwide annual supply of industrial robots 2000 - 2018*[13]

The large increase in industrial robots are a product of many factors, but one of them is the diverse usage of technology alongside the advancements within this field to automatize new areas. A study done at Oxford University in 2013 by Carl Benedikt Frey and Michael Osborne, exemplified in figure 5.2, predicts that a wide range of occupations will almost certainly be automatized within the near future. The study uses an advanced algorithm developed by the authors to determine the chance of computerization within a certain job field. According to the study more than 46 % of the current jobs in USA could be computerized in the next 10-20 years. Figure 5.2 only shows a brief glimpse of different project related jobs, in the context of industrial manipulators, but the full range of the study is wast and leaves an impression of the great diversity in computerization[14]

Grinding and polishing workers, hand.	97%
Electrical and electronic equipment assemblers	95%
Industrial truck and tractor operators	93%
Patternmakers, metal and plastic	90%
Laborers and freight, mtock, and material movers, hand.	85%
Printing press operators	83%
Cooks, fast food	81%
Bartenders	77%
	58%
Percentage/probality of automation	

Figure 5.2: Oxford study; chance of computerization[14]

The future of robotics is up to some extent predictable, for this technology is more present than ever. While robots can free resources, help a production, replace repetitive work and contribute to ease the employees assignments or prevent them from taking hazardous tasks, it is also true that they can take the jobs from people of a lower education level and leave vacant positions for engineers or higher educated workers, therefore, an ethical dilemma arises; because by trying to improve the quality of life of the employees and encouraging future generations to be fully educated; right now the point of transition is faced where the current workers are being left without jobs.[14]

Nevertheless, in some cases e.g. at Grundfos, robotics have helped their production and did not reduce the need for employers (as seen in section 3.1.2). Therefore it could be relevant to investigate the relationship between machines and their users. The next chapter looks at how humans interact with robots, how and what can be learned from this.

6 Human Robot Interaction

In order to ease the repetitive tasks assigned to humans, these kind of jobs are usually being taken care of by robots, which can perform better, faster and with minimal risk of harming themselves. When robots are introduced into the working environment, they must interact with the employees, which is why Human Robot Interaction becomes relevant.

Human Robot Interaction (HRI) is a "field of study dedicated to understanding, designing, and evaluating robotic systems for use by or with humans"[15]. Therefore, in order to interact, there must be some sort of communication between the robot and the human which is usually distinguished as proximate or remote interaction. These two different categories emerge due to the need of differentiating human behavior and the nature of communication depending on the distance of their interaction.

Remote interaction is defined in the form that the actors of communication are not co-located spatially or even temporally, resulting in a rather supervisory task from the human towards the robot. A good illustration of this sort of interaction is the relationship between the Mars Rover and its users.[15] Proximate interaction, implies a common work environment which can lead to a physical interaction or even a social one, in the sense that humans and robots are regarded as peers or companions. A clear example is the interaction which takes place between industrial manipulators and their co-workers.[15]

Having defined the two main categories which differentiate the nature of communication and human behavior that can take place, it becomes clear that when having a proximate interaction with machines, humans have to take several precautions to ensure the highest level of safety. This can be done with training, instructions on every machine or proper guarding of dangerous machines. A study conducted in Finland, ranked high in international robot density statistics which have similar statistics as found in Europe,[16] shows in which areas severe accidents happen and how often they occur. Figure 6.1 shows the number of severe accidents involving either a “robot” or “manipulator” in the time period between 1989-2006, where the first relevant case was in 1989. With 3 fatalities in the years 2000, 2005 and 2006 all with the victim being crushed. All following statistics are taken from The Accident Report Database (TAPS) of the safety Administration in Finland.[16]

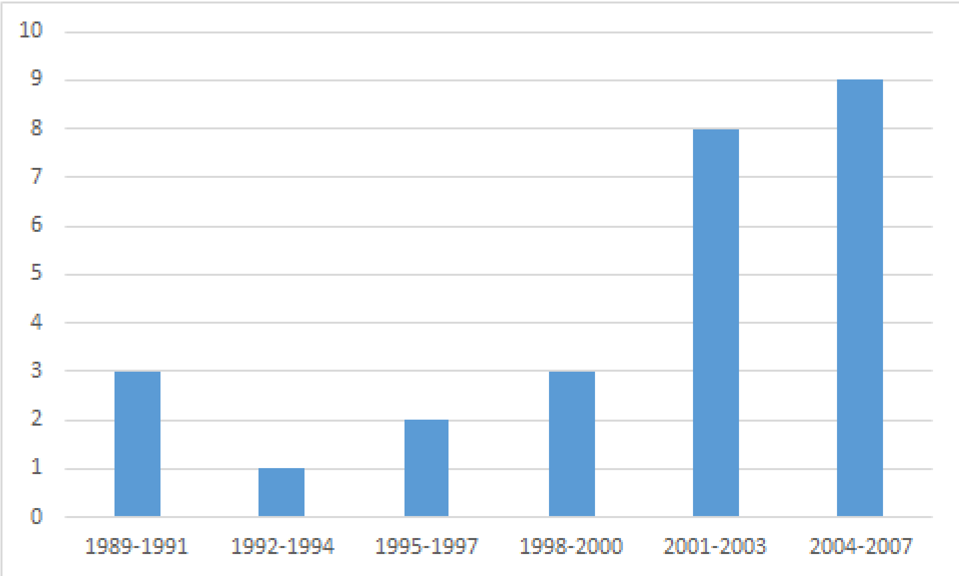

Figure 6.1: A total of 25 severe robot-related accidents between 1989-2006 in Finland.[16]

As seen in the graph it is clear that the number of accidents has risen since entering the new millennium, which correlate with the increasing supply of robots in the industrial work field. This may not seem like a lot of injuries, but considering the high standard in the field, 16 severe accidents with 3 of them being fatal is fairly high. The accidents can be classified according to their cause or causes, each accident can have more than one cause. Figure 6.2 shows in which operation mode accidents occurred and how often. Horizontal are the different operating modes and lateral is the causes. [16]

Operating modes/cause	Total	Trouble shoot-ing	Repairing and maintenance	Produ-ction	programing,adjust-mens,cleaing, Setting, tool change	Undefined task
Total (number of accidents)	25	12	1	5	6	1
Total %	100%	48%	4%	20%	24%	4%
Unexpected start-up	9	5	0	2	2	0
Mishaps	5	3	1	0	1	0
Dangerous working method	11	6	0	1	4	0
Inadequate safeguarding	19	8	1	4	5	1
Inadequate design	9	1	1	1	5	1
Inadequate work experience	6	3	1	2	0	0
Failure	1	1	0	0	0	0
Poor visibility	0	0	0	0	0	0
Insufficient warnings/instruction	15	8	1	3	2	1
Haste	3	2	0	0	1	0

Figure 6.2: Quantity of severe accidents in different operating modes according to the cause or causes.[16]

Looking at 6.2 almost 50% of the accidents involve troubleshooting and there are often several factors that contribute to injuries. Taken the total number of all the accidents inadequate safeguarding is almost 80% of accidents with insufficient warnings/instructions being a close second.[16] Almost all of these accidents should be preventable with clear regulations and instructions for both the designer and the people working alongside the robots.

	Quantity	% of all the accidents
Robot movement or operation	23	92%
Handling of objects and tools	1	4%
Moving, slipping, distortions	1	4%

Figure 6.3: Accidents according to their cause or consequences[16]

As shown in the figure 6.3 most of the accidents involve robot movement or operation and should be the main area to improve regarding the safety of workers seen from an integrators perspective. Most of the causes for these accidents have been put into regulations in Denmark to prevent these. These are all things to consider when building a robot for industrial purpose and they should be used as a guideline to avoid repeating the same pitfalls. All these safety hazards have lead to some general regulations most countries have implemented.

Such laws were made in Denmark in 1995 the “At-anvisning nr. 2.2.0.3 af November 1995” which was replaced in 2005 by “At-vejledning B.1.4” and is currently the one in use.[17] Denmark being a part of EU also abides to: 89/391/EEC directive for safety and health of workers at work. 2009/104/EC ”Work equipment” describing the employer is responsible for work equipment is suitable for the work, without impairment to their safety or health. When is it not possible to ensure those criteria the employer shall take action minimize the risks. [18]

The Instructions applies to industrial manipulators, driver-less trucks, CNC-machines and other automated machine installations. General regulations involving automatic machine installations including the individual units shall be arranged so they can be transported, installed, used and maintained safely and without any risks to the health of workers. [17] When a manipulator is fenced in the door must be electronically monitored. An example of this can be seen in figure 6.4 where the workspace includes conveyor belts, safety fence and an electrical door.

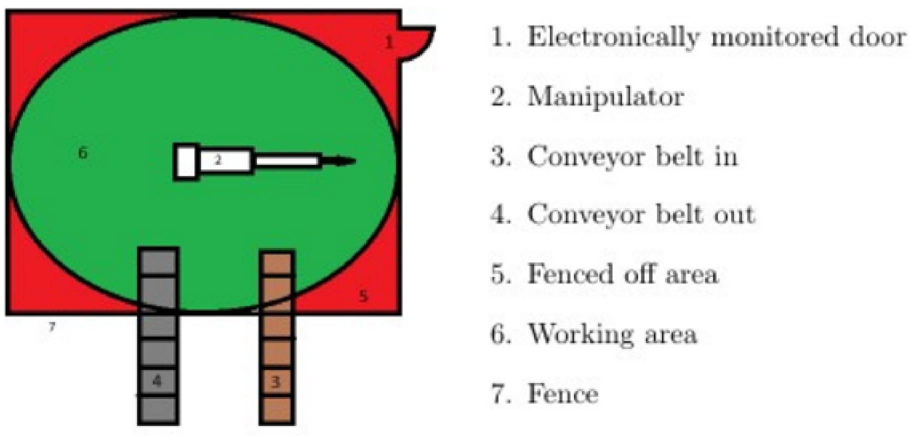

Figure 6.4: Example of a workspace with a manipulator.

While the regulations states that there must be fencing to ensure security for the workers. However in 2006 the directive 2006/42/EC from the European parliaments, on machinery was created. In this it is stated that the manufacturer of the machinery must conduct a risk assessment to conclude on the health hazards and risks involved in operating the machinery and then they must construct the machinery to reduce those risk. If the risk cannot be reduced then there must be clear information on what precautions is needed for safe operation.[19]

This means that within the software of the machinery, the manufacturer can include safeguards to ensure the safety of the operators, therefore minimizing the need for fencing as long as the manipulator itself have the proper safety measures to ensure the protection of the workers.[19]

For construction and equipment there are some general requirements[19], such as: If the manipulator suffers from loss of energy it cannot be performing any kind of action that could lead to injuries of a person, and the same with a sudden return of energy. External disturbances such as electric and magnetic fields, light, temperature, humidity, air pressure and dust cannot affect the safety functions of an industrial manipulator. The system must include an indicating device, which by dangerous malfunction shows where the error occurred. Safety functions which are involving personal safety include emergency stop devices, stop functions that limits the range of motion, stop functions from the outer protection device such a video surveillance, a light curtain, light beams, contact plates, etc. this will help to protect personal if they do not take the proper precautions before entering an industrial manipulators workspace.[17] After a stop the industrial manipulator has to be programmed in such a way that it will start/stop in a safe way. This is both a production and a safety measurement as a troublesome restart may give rise to circumvent security measures.[17]

Some of these regulations are the fundamentals when working on a solution. The solution should not only meet the requirements of the employer but focus heavily on the safety of the worker. This is one of the factors when deciding which system is chosen.
Within this section there are certain things that can be taken as parameters in the requirements, while industrial manipulators need to have fences and safety measures to ensure the safety of the workers, in the 2006 EU directive on machine safety, it was allowed to implement the safety measures through the construction of the manipulators itself. Therefore, since the aim of this project is to provide Grundfos with a manipulator able to work in close terms with their employees as well as being able to be relocated when it is not being used in a specific work station, the manipulator needs some way of ensuring the safety of the worker within its

software itself. For this project the EN ISO 10128-1 risk assessment of collaborative robots is conducted on a posterior chapter to evaluate the viability of the solution.

As part of this chapter, the regulations, safety needs and human interaction with the manipulator have been researched. It can be concluded that the manipulator can be implemented within the workstation, without fencing if it can be deemed safe for the worker. This would involve some form of safety mechanism implemented within the software of the manipulator. This concludes the analysis that has been conducted and gives the prerequisites needed to create the proper requirements for the solution.

7 Requirements

7.1 Introduction

The purpose of these product requirements, is to specify the requirements for this technical solution These requirements are made for the costumer of this project, Grundfos and the supervisors of the group.

Definitions

UR5 = Universal robot 5

GUI = Graphical user interface

QC = Quality control

TCP/IP = Transmission control protocol/Internet Protocol

Index of Product requirement.

11.1 Introduction

11.2 General description

11.3 External interfaces

11.4 Performance requirements

11.5 Quality requirements

11.6 Design requirements

11.7 Other requirements

11.8 Deliveries

The purpose of this project is to reduce the repetitive manual work within a particular workspace. This is done by implementing an industrial manipulator within the workspace to compensate the operator, by handling the rotors in the process.

Any changes to the requirements is done, through discussion in the development team and with the groups supervisor.

As a preparation for the requirements for the product, a problem analysis was conducted, all specific requirements are extracted from the problem analysis.

7.2 General Description

Description: The current system as described in chapter 3.1.2, handles the base part of a rotor. The item is retrieved from conveyor belt by the operator, visually quality checked, then put through the different stations of the work station, and lastly palletized. The new system handles the rotor from the conveyor belt, all the way trough placing the finished rotor systematically on a pallet. This is done by implementing a robotic system in the center of the work station exemplified in figure 7.1, while upholding the same production standards in the work station as currently being used.

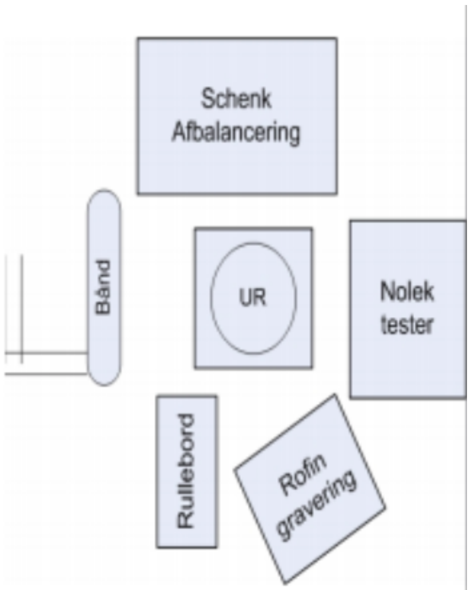

Figure 7.1: Preliminary outline of the cell

Product Perspective: The manipulator uses a normal household block for power-source.

The manipulators GUI suffices as user interface for interacting with the system. The Operator is required to start and stop the system, do the necessary QC tests, plus replacing filled pallets. The manipulators payload can handle the rotors and repeatability is accurate enough for the system.

Product Functions: The manipulator is placed in the center of the work station interacting with the different stations; the Schenk de-balancing, Nolek leakage testing, Rofin engraving, and the pallet. In the following list, one can see the desired end goal for how a manipulator should operate in this station.

- Start
- A manipulator places item 1 from conveyor in Schenk drawer
- A manipulator closes the drawer in the Schenk
- A manipulator moves item 1 from Schenk drawer to the Noleks holder
- A manipulator places item 2 from conveyor in Schenk drawer
- A manipulator closes the drawer in the Schenk
- A manipulator moves item 2 from Schenk drawer to the Noleks holder
- A manipulator activates the Nolek
- A manipulator places item 1 from Nolek to Rofin
- A manipulator activates Rofin
- A manipulator retrieves item 1 from Rofin and palletizes on trolley
- A manipulator places item 2 from Nolek to Rofin
- A manipulator activates Rofin
- A manipulator retrieves item 2 from Rofin and palletizes on trolley
- Stop

User Characteristics: It is assumed that the operator has no experience for operating or working alongside the manipulator, but has experience with the work station.

Constraints: The manipulator has a reach of 850 mm and that is not enough to reach the different stations all by it self.

Assumptions and dependencies: The developed tool gripper is able to uphold relevant CE standards. The QC Rotor tests will not be done in this project, but suggestions and considerations are laid out. When the pallet is full it is replaced by a empty one. A standard UR5 including the software is being used to solve the case. An internet connection is available if needed. The CO_2 emissions are acceptable. A gripping tool for the manipulator to safely handle the rotors was developed.

7.3 External Interfaces

In order to create a flexible work station, the chosen manipulator should be able to operate with common household current (230VAC). Seeing as this task is centered in Denmark, the inlet should be of the type K and comply with DS 60884-2-D1 [20].

If an internet connection is needed in order to create an viable solution, the chosen manipulator should support TCP/IP.

7.4 Performance Requirements

The following performance requirements have been identified, the manipulator lift capacity, requirements related to the dimensions of the workstation and the cycle time at the different stations. All of the performance requirements are static. The specific requirements are as follows:

- The manipulator has to be able to lift the heaviest rotor(1.1kg) and the end effector.
- The manipulator has to be able to reach from conveyor belt to the de-balancing station.
- The manipulator has to reach from the de-balancing station to the leakage station.
- The manipulator has to able to reach from the leakage station to engraving station.

- The manipulator has to reach from the engraving station to the pallet.
- The manipulator has to be able to produce at least 40 rotors in 60 minutes.

7.5 Quality Requirements

One of the most important values Grundfos has, is the sustainability, both in regards to the environment, but also in a social context. Therefore it is important that all involved partners are complying with corporate social responsibility (CSR). From CSR, four key points can be extracted for the requirements, these are as following;

- The work station as a whole, shall not pose a threat to the operator.
- The repetitiveness of the work station shall not exceed low repetitive (as described in chapter 4, repetitive work).
- The emission of CO_2, shall not exceed more than a third of the average annual emission of a human being.
- Uncertified labor should not be used (e.g. child labor).

7.6 Other Requirements

There still are some other aspects the solution must fulfill in order to be a valid solution. As stated in chapter 6, the manipulator must comply with a number of legal aspects, especially those which involve the safety of humans. If not, the manipulator would not be able to collaborate with the workers and this would be threatening Grundfos' values explained in 3.1.1.

- The Manipulator must be implemented in such a way that fences will not be required around the manipulator.

The manipulator may not only be used in one area ans should be easy to move around for the customer

- The manipulator must be flexible, meaning that installation and programming of the manipulator should take less than 3 hours.

Because of Grundfos being a responsible company, the manipulator has to follow the current standards and try to be up front with any new changes

- The manipulator must fulfill relevant ISO standards.

7.7 Deliveries

The deadline for this project is the 24th of May 2016.

This involves the full documentation and prototype development. As part of this project a working prototype has to be produced. CAD Model and kinematic calculations, was made in order to document the work.

At the 1st of May, the first draft of the prototype was done. This was evaluated with a test to see the progress, leading to an evaluation of the progress and a planning of any changes that needs to be done, for the duration of the working time. Besides from these overall deadlines, a weekly status was held to evaluate the process on a small scale level. At the 9th of May, Grundfos was represented and the prototype showcased for feedback.

7.8 Acceptance Criteria

Before making an acceptance sheet, delimitations have to be made on this project this is done as to not make the goal of the project impossibly large. What that means is that all the requirements that can not be tested for different reason are not be taken into consideration. First thing that have been delimitated is that only one manipulator is be used during the online testing, this is a decision that have been made because there is only one manipulator at our disposal. Another aspect in which this study is delimitated is in regards to CO_2, where there is a requirement of how much CO_2 the manipulator should be allowed to produce, but because there is no accurate means of measuring the CO_2 emission though an estimate could be made. This delimitation is related to quality requirements. With the requirements delimitated, an acceptance sheet can be produced. The following table serves as such.

Acceptance test specifications			
Requirements	Criteria	How to Test	Pass/fail
TCP/IP	Able to connect to the internet.	Check for TCP/IP capabilities on the manipulator.	
Payload	Able to lift the heaviest of the rotors, weighing 1,1 kg.	Have it lift the heaviest rotor.	
Range – Conveyor	Able to reach the Conveyor belt with the incoming rotors.	Measuring the distance the manipulator can reach.	
Range – De-balancing station	Able to reach the de-balancing station.	Measuring the distance the manipulator can reach.	
Range – Leak station	Able to reach the leak station.	Measuring the distance the manipulator can reach.	
Range – Engraving station	Able to reach the engraving station.	Measuring the distance the manipulator can reach.	
Output	Able to produce 40 units per hour.	Time how fast it takes for one work cycle and scale it up to one hour.	
Safety	Unable to harm a person.	Test impact force.	
Fencing	Able to work without a safety fence round it.	Check if the there is a stop function	
Low repetition	Must not require workers to perform repetitive work in order to function.	Time if one work cycle takes longer than 30 seconds.	
CO_2 emission	Must not exceed more than a third of what an average person emits per year.	Through Calculation an estimate is made.	
Uncertified labor	Must not have any involvement with uncertified labor.	Check if the manufacturer uses uncertified labor.	
Flexible	Able to install and setup within 3 hours.	Research information from manufacturer	
Legality	Follows standards.	Check if it follows relevant standards	

This is be the checklist for the final solution. Tests are done in every area to make sure everything works as intended. And a final test is be conducted to ensure the product works as the customer ordered.

7.9 Final Problem Statement

How can a viable solution that reduces repetitive work while complying with the acceptance criteria be set up?

8 Universal Robots

As a part of the project theme ”UR-robot in production set-up” and to commend the wish of Grundfos to use standard robotic solutions because of availability, this projects chosen manipulator is from the company ”Universal Robots”.

Universal Robots is a company located in Denmark, that was founded in 2005 by Esben Østergaard, Kasper Støy and Kristian Kassow. A few years earlier, the three founders came up with the idea to create a light-weighted easy operated robot, while working on robots in the food industry. Having small and medium-sized enterprises in mind, the company's first manipulator, the UR5, was launched in 2009. The UR5 would impact the robotics market by the new approach to industrial manipulators with its low cost and weight (plus the safety protocols)[21]. At the present day, Universal Robots are selling its products worldwide and have expanded their company several times and the company continually keeps inventing new robotic solutions in terms with the original goals. In 2015, Teradyne, a large company who specializes in automatic test equipment and automation bought the company[22]. Universal Robots are still under the same management and headquarters remain in DK after the requisition[22]. In 2015 Universal Robots made it to the 25th place on MIT Technology Reviews list over the 50 smartest companies.[23]

8.1 Sustainability Policy

As a part of Grundfos sustainability policy, partners and products are expected to follow certain environmental ethical guidelines(see section 3.1.1). Universal Robots, as a company owned by Teradyne, believes and advocates corporate social responsibility (CSR)[24], meaning their business model and code of conduct is underlined by the essence of the relevant law, combined with ethical standards. In function this means generating a profit in a globally responsible way with the future of the planet in mind. Exemplified Universal Robots aim to provide high quality products made under the best conditions. They do not use child or forced labor and believe in creating a healthy working environment[22]. They keep contracts with all employees and do not underpay.[22] Furthermore any partner or partners' partner is expected to uphold the same high ethical standards.[22][24]

8.2 On-line Programming

Universal Robots manipulators can be programmed on-line on different levels. The first is using the teach pendant(in other words through GUI) that allows movement of robotic manipulator to where it needs to move and in the way it is needed (e.g. repeating actions). Other one is through script programming, mostly using python language (other languages can be used, like C++ e.g.).[21][25]

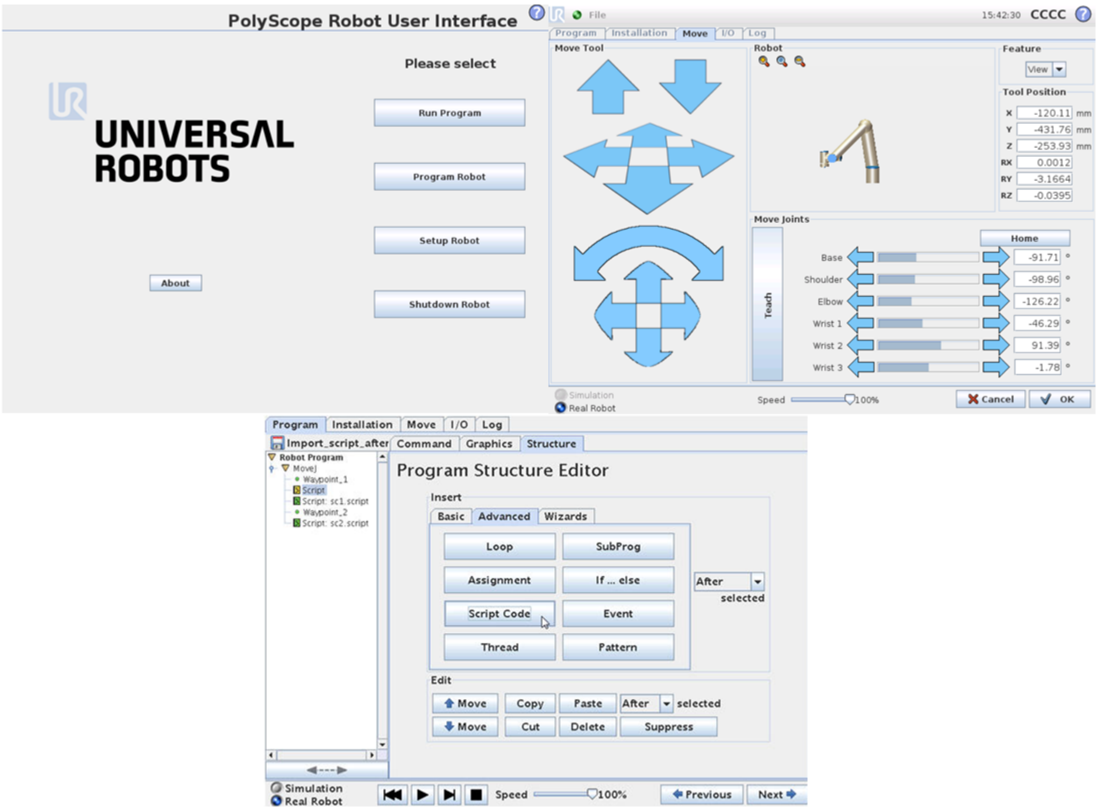

Figure 8.1: On-line programming interface of UR[21]

In figure 8.1 can be seen the PolyScope, which is the graphical user interface for Universal Robots. The interface also allows for setting up initialization, has on-screen editors and different Setup Tabs for manipulating the manipulator:

- **Move Tab**: On this tab the manipulator can be moved directly, either by translating/rotating the robot tool, or by moving different joints of the manipulator individually
- **I/O Tab**: On this tab live I/O signals can be monitored and set from or to the manipulator.
- **AutoMove Tab**: This tab can be used when the manipulator needs to be moved to a specific location in its workspace. An example can be when the manipulator has to move to the start position of a program before running it.
- **Other Tabs**: Load, save, Tool Center Point and setup screens(e.g. I/O setup, default program setup and etc.) tabs.[26]

GUI programming itself is done by setting up waypoints, gripping and releasing moments, also repeat, delay, stop moments, speed. Most of them are done through Command Tabs, for example, the Action Tab, where the programmer can set either digital or analog outputs to a given value(it can also be used to set the payload of the manipulator).[26]

As mentioned before, there is also **script programming**. Script can be imported and exported usually in Python language. This script consists of same things like waypoints, movements and etc., but can be exported from manipulator and into manipulator, which allows easier and efficient switching between on-line and off-line programming(e.g. working on simulation)[25].

8.3 Comparison of Manipulators

This table 8.1 is comparison of the three similar in workload manipulators - UR5, UR10 and KUKA LBR IIWA 7 R800. Working radius of the UR10, as can be seen, is significantly bigger compared to the UR5 and KUKA, which can be good in the workstation (the more the reach, the more different type of work can be done). Payload of the manipulators differs in 2-3 kg, but as known for this project, there is no need for too big of a payload, since the rotor does not weigh too much (1.1 kg). Amount of the axis represents safety and possibilities(e.g. avoiding obstacles), but the 6-axis manipulator UR5 and UR10 can be as well as good as the 7-axis KUKA

Table 8.1: UR5, UR10,KUKA LBR IIWA 7 R800 comparison[27][28][29]

	UR5	UR10	KUKA IIWA
Working radius	850 mm	1300 mm	800 mm
Payload	5 kg	10 kg	7 kg
Weight	18.4 kg	28.9 kg	23.9 kg
Footprint	149 mm	190 mm	136 mm
Axis	6 axis	6 axis	7 axis

LBR IIWA 7 R800, because of the work that does not require 7-axis(e.g. transporting rotor). The KUKAs LBR IIWA footprint is smaller than the UR10s and UR5s - the smaller the footprint, the easier to change structure of the workstation. As conclusion, UR5 is a good choice almost in everything, but UR10s working radius is bigger and that is needed to reach different stations. KUKA is optimal, but has unneeded axis and smaller working radius than UR5, which does not mean that it is bad(e.g. footprint is smaller), but additional cost and problems may be caused.

8.4 Choice of Manipulator

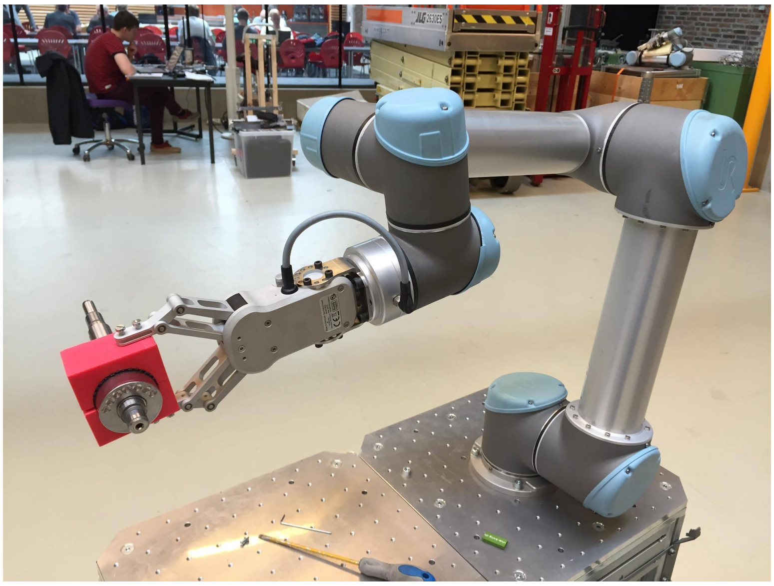

Figure 8.2: The UR5

Multiple reasons lead to choice of the UR5: its compatibility with the human interaction since one of the projects goals is based on making the workstation safer for the one working with it(i.e. being able to remove fence), its workspace, footprint, axis, payload and additionally we were not given much of alternatives as well

The UR10's torque in the joints is between 56Nm, 150 and 330Nm compared to the UR5s torque, which varies between 28Nm and 150Nm in the joints[30], which might make the UR10 a greater risk of harm people working with the manipulator. As conclusion because of UR5s torque and size the manipulator poses minimum threat to the one interacting with it. Footprint, axis, payload - everything is optimal. The UR5 does not take a lot of space, which means it fits in the workstation. The manipulator is 6-axis, which allows all needed interactions. Payload is enough to lift rotor. But once again, workspace is far too small and to reach workstations, there needs to be two UR5s. Otherwise, if there was possibility, UR10 would be chosen as projects manipulator to reach all workstations without using two manipulators.

9 Solution

The solution proposed for this project is divided in several subsections which describe different aspects that were approached and which, combined, result in the final idea chosen to solve the issue presented.

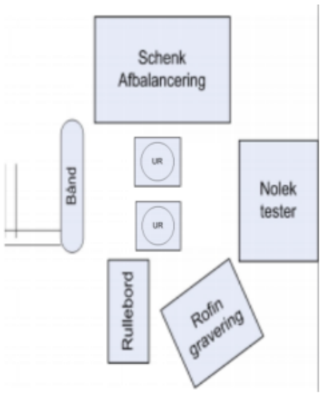

Figure 9.1: Working Station with two URs

Part for the solution is the need of a proper gripper which is capable of adequately holding the cylindrical rotors. Therefore, a two finger gripper was modeled and 3D printed. Once attached to the manipulator, it has a parallel motion, which, although it can be expensive when compared to the angular grippers, it is also easier to design and program. The gripper was designed in a way that, when the two fingers close in parallel, its shape encompasses the rotor and holds it with friction. In order to increase the viability of this solution, the interior of the gripper which is in contact with the rotors was covered with a non-slipping surface. Regarding the mathematical study of the project, a kinematic analysis was developed. This task was divided in three sections:

- First the forward kinematics was covered, this computes the position of the end effector from specified values for the joint parameters. In order to proceed, the selected frame of reference for the robotic application was the Denavit-Hartenberg convection.

- Inverse kinematics as the name states, is the opposite process of the one stated above and its purpose is to compute the joint parameter to achieve a specified position of the end effector.

- Finally, a trajectory generation was developed to show the methods which compute a trajectory in multidimensional space, this way an insight of the movement the manipulator is following can be gained.

In order to virtually represent the objects that are used in the simulation, the rotors provided by Grundfos and some stations were converted into a CAD model. As well as the prototype of the gripper, which was first designed as model before it was 3D printed.

When developing an idea, a simulation is usually a key point due to the fact that they not only help both, costumer and developers to gain a better insight of the project and how performs or is designed, but it also can prevent issues such as inconvenient speeds or exceeded pressures on the real product. Therefore, using RoboDK a simulation was carried out.

The solution must coincide with some safety regulations, therefore a risk assessment is carried out to estimate the recognized threat the manipulator could suppose to humans.

Finally, once all the previous tasks are achieved, an acceptance test must be done to prove that the solution meets the requirements and it is able to perform as expected, otherwise the solution should be adapted or changed.

9.1 Kinematics

The reason for doing kinematics of a manipulator is to transfer it to online programming and simulation, where the trajectory was tested and then, if needs be, kinematics and Denavit-Hartenberg parameters was reworked. It will provide a mathematical model of how the UR is going to move and it is in that way that it is used, the inverse kinematics will provide the joint parameters for a desired point. This was helpful moving forward with trajectory plans.

9.1.1 Forward Kinematics

The first step that is needed in the forward kinematics is finding the Denavit-Hartenberg parameters from now on referred to as DH-parameters. To find the DH-parameters, the UR-5 has to be put in zero position and the measurements for it will have to be taken. Then with the UR-5 in its zero position the coordinate systems are placed on the manipulator. Seeing as it is a simple open-close gripper that is used, it is not necessary to consider the gripper when placing the coordinate systems, though it would have been necessary had a more complicated gripper been used. After the coordinate systems has been placed it was possible to find the DH-parameters, with the measurements taken for the UR-5, which is given by the following:

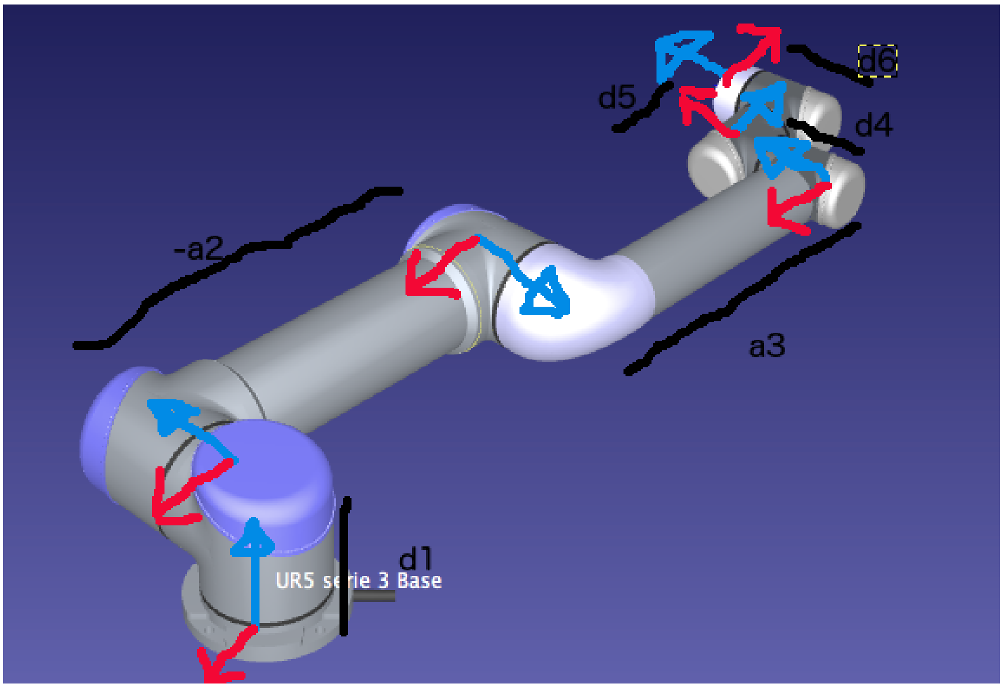

Figure 9.2: Coordinate frame assignment for the UR5

Figure 9.2 shows the denavit-hartenberg frame assignment for the UR5.

i	θ_i	d_i	a_i	α_i
1	θ	89.2	0	$\frac{\pi}{2}$
2	θ	0	-425	0
3	θ	0	-392	0
4	θ	109.3	0	$\frac{\pi}{2}$
5	θ	94.75	0	$-\frac{\pi}{2}$
6	θ	82.5	0	0

Table 9.1: Denavit-Hartenberg Parameters for the UR-5

Where θ is the angle from $x_i - 1$ to x_i measured about z_i, d is the distance from $x_i - 1$ to x_i measured along the z_i, a is the distance from z_i to $z_i + 1$ measured along x_i and finally alpha is the angle from z_i to z_{i+1} measured about x_i. The distances $a_i - 1$ and d_i are given in millimeters while the degrees in θ and α are given in radians.

With the DH-Parameters figured out it can be put into a four by four transformation matrix, which was of a coordinate system from the previous coordinate system that came before it. With that it is possible to compute the forward kinematics with the following equation:

$$T_6^0 = T_1^0 T_2^1 T_3^2 T_4^3 T_5^4 T_6^5 \tag{9.1}$$

where T is the transformation matrix for the different coordinate systems where the result of all of them was a transformation matrix describing the end-effector position relating to the base.

Plotting the DH-parameters into the homogeneous matrix T_j^i gives the following transformation matrix, which is the transformation from one coordinate system to the previous coordinate system:

$$T_i^{i-1} = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) & 0 & a_i \\ \sin(\theta_i)\cos(\alpha_{i-1}) & \cos(\theta_i)\cos(\alpha_{i-1}) & -\sin(\alpha_{i-1}) & -\sin(\alpha_{i-1})d_i \\ \sin(\theta_i)\sin(\alpha_{i-1}) & \cos(\theta_i)\sin(\alpha_{i-1}) & \cos(\alpha_{i-1}) & \cos(\alpha_{i-1})d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9.2}$$

Computing the above matrix for each T_j^i and then multiplying them as shown in the above equation 9.1 will give the homogeneous matrix that is the solution for the forward kinematics. The matrix computed was of the following form:

$$\begin{bmatrix} x_x & y_x & z_x & (P_j^i)_x \\ x_y & y_y & z_y & (P_j^i)_y \\ x_z & y_z & z_z & (P_j^i)_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9.3}$$

Where P is the coordinates for the end-effector pose that is the goal to find with the forward kinematics. When using Matlab it is possible to find the following homogeneous matrix for the forward kinematics that is the final result in the process of finding the forward kinematics:

$$T_6^0 = \begin{bmatrix} 1.0000 & 0 & 0 & -0.8170 \\ 0 & 0 & -1.0000 & -0.1914 \\ 0 & 1.0000 & 0 & -0.0052 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix} \tag{9.4}$$

This homogeneous matrix gives as stated above the end-effector pose which is what that needed to be found with the forward kinematics, more precisely the pose of the end-effector is the last column in the above matrix, -0.8170, -0.1914, -0.0052 and 1.0000. The forward kinematics is computed for the manipulator in zero position. With the forward kinematics done the next part will go into inverse kinematics.

9.1.2 Inverse Kinematics

All figures in the following inverse kinematics is taken from the same source, and so is the approach[31]. Having the forward kinematics gives as said the pose for the end-effector, on the other hand with the inverse kinematics it is possible to calculate the joint coordinates the manipulator needs in order to reach a known Cartesian pose.

Before starting on the inverse kinematics it is important to first figure out which approach that was used to find a solution, if it is going to be the closed-form solution or a Numerical Solution. Since the UR-5 do not have a spherical wrist and that is a requirement for using the closed-form solution this will not be used, but rather the numerical solution.

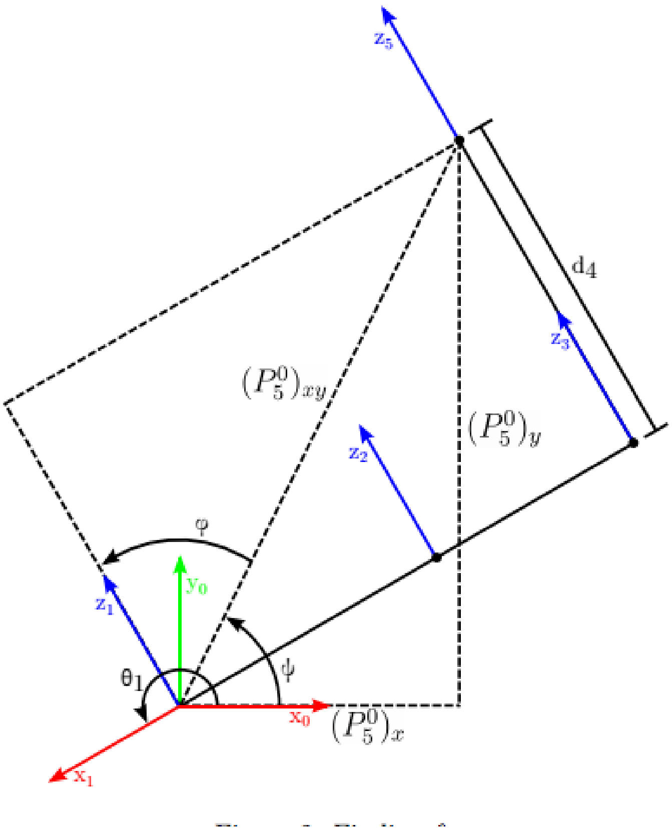

Figure 9.3: Finding θ_1 [31]

As said the inverse kinematics will give joint coordinates for the UR5 where every θ is a joint coordinate and denotes a different position for the shoulder, elbow and wrist of the UR5. The first step is to find θ_1, to find θ_1 the fifth coordinate was found with respect to a vector called P_5^0 the following vector is computed the following way:

$$P_5^0 = T_6^0 \begin{bmatrix} 0 \\ 0 \\ -d_4 \\ 1 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{9.5}$$

With the vector computed it is possible to calculate θ_1 with the following formula, where the angles ψ, ϕ and $\frac{\pi}{2}$ are added together, that are derived from figure 9.3 that are a 2d drawing of the UR5 from the base to the fifth coordinate:

$$\theta_1 = \psi + \phi + \frac{\pi}{2} \tag{9.6}$$

Where ψ is the angle from x_0 to $(P_5^0)_{xy}$ and ϕ is the angle from $(P_5^0)_{xy}$ to z_1 which can be seen in figure 9.3. ψ is equal to:

$$\psi = \arctan 2((P_5^0)_y (P_5^0)_x) \tag{9.7}$$

which can be rewritten on the form because $\arctan 2$ is an $\arctan$ function with two inputs.

$$\psi = \arctan(\frac{(P_5^0)_y}{(P_5^0)_x}) \tag{9.8}$$

ϕ can as ψ be rewritten from

$$\phi = \pm \arccos \frac{d_4}{(P_5^0)_x y} \tag{9.9}$$

to,

$$\phi = \pm \arccos \frac{d_4}{\sqrt{(P_5^0)_x^2 + (P_5^0)_y^2}} \tag{9.10}$$

Because of ϕ it can be seen that there is two solutions for θ_1, where one is for when the shoulder is left and the other is for when the shoulder is right. The next step after finding θ_1 is to find θ_5 and to do that, There was looked at the 6th frame from the first frame which means T_6^1 for the purpose it was a vector called $(P_6^1)_z$ it is possible to compute θ_5 with the equation that is derived from the figure9.4 that are a 2d drawing of the UR5 from the first coordinate to sixth coordinate:

$$\theta_5 = \pm \arccos(\frac{(P_6^1)_z - d_4}{d_6}) \tag{9.11}$$

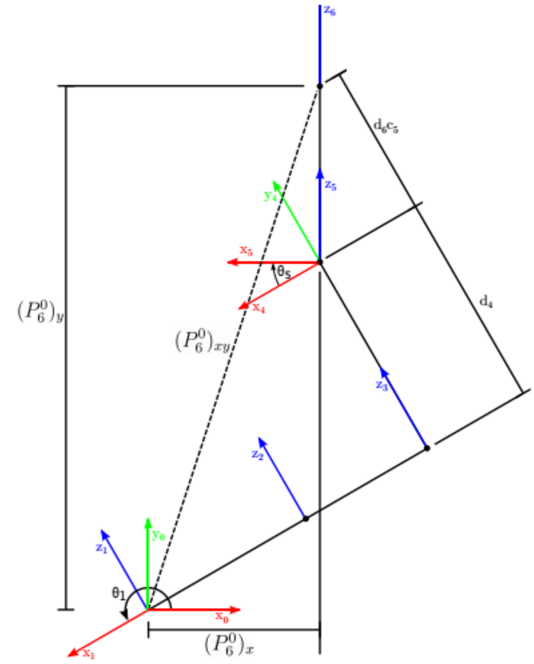

Figure 9.4: Finding θ_5 [31]

As with θ_1 again there are two solutions this time for θ_5, the two solutions are for the wrist either being up or down. With θ_5 calculated the next θ to compute was θ_6. This time the sixth joint was considered from the first joint T_6^1. To find θ_6 the following equation was used:

$$\theta_6 = \arctan 2(\frac{-z_y}{\sin(\theta_5)}, \frac{z_x}{\sin(\theta_5)}) \tag{9.12}$$

Which is isolated using these two equations:

$$-\sin(\theta_6)\sin(\theta_5) = z_y \tag{9.13}$$

and

$$\cos(\theta_6)\sin(\theta_5) = z_x \tag{9.14}$$

where θ_6 is isolated in both and after that they are put into the final equation as seen in equation (9.12). As with the other arctangent functions that has been used earlier with two inputs this can also be written on another form, which is:

$$\theta_6 = \arctan(\frac{\frac{-z_y}{\sin(\theta_5)}}{\frac{z_x}{\sin(\theta_5)}}) \tag{9.15}$$

It can be seen that there is an infinite number of solutions when any of the values in the equation is equal to zero. With the first three θ computed, it is now possible to find θ_1, θ_2 and θ_3. This can be done seeing it as a simple 3R manipulator, which will make it easier to solve for the remaining θ. First θ to solve was θ_3 but first it has to be determined which coordinate frame, should be looked at and from where. Since it is a 3R manipulator it was from the T_3^1. Figure 9.5 was used to derive the formulas used the figure shows three joints from first coordinate to the third.

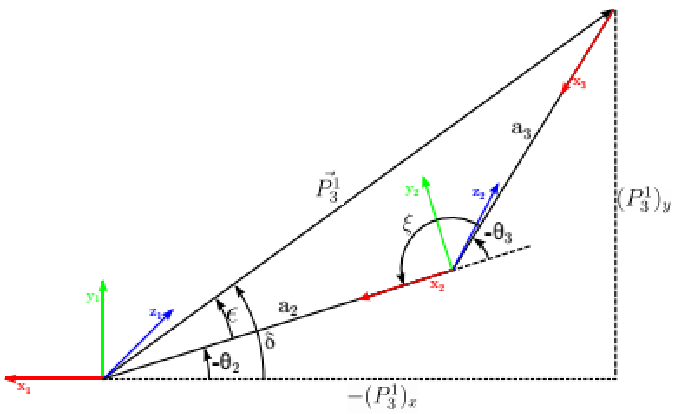

Figure 9.5: Finding θ_2 and θ_3 [31]

The formula used was:

$$\cos(\xi) = \frac{||\vec{P_3^1}||^2 - a_2^2 - a_3^2}{2a_2a_3} \tag{9.16}$$

Where ξ is the angle from $-\theta_3$ to x_2 and $\vec{P_3^1}$ is a vector that goes from first coordinate system to the third when looking at the three joints as a simple 3R manipulator. Using the law of cosine, the following formula is found combined with the previous equation that is used to find θ_3

$$\theta_3 = \pm\arccos(\frac{||\vec{P_3^1}||^2 - a_2^2 - a_3^2}{2a_2a_3} \tag{9.17}$$

It can also be seen that θ_2 can be computed by the following formula:

$$\theta_2 = -(\delta - \epsilon) \tag{9.18}$$

Where δ is the angle from $-(P_3^1)_x$ to the vector $\vec{P_3^1}$ and ϵ is the angle from a_2 to the vector

$\vec{P_3^1}$. δ is computed on the following formula

$$\arctan 2 = ((P_3^1)_y, (P_3^1)_x) \tag{9.19}$$

and ϵ is computed by the law of sines which is

$$\frac{\sin(\xi)}{||\vec{P_3^1}||} = \frac{\sin(\epsilon)}{a_3} \tag{9.20}$$

, which will give a final formula for θ_2 to where the two solutions will show the position of the elbow to either to be up or down. The final equation for θ_2 is:

$$\theta_2 = -\arctan 2((P_3^1)_y, (P_3^1)_x) + \arcsin(\frac{a_3 \sin(\theta_3)}{||\vec{P_3^1}||}) \tag{9.21}$$

Now that θ_2 has been computed , only θ_4 is remaining, in order to calculate this, first the T_4^3 is computed and from that the following arctangent equation with two inputs can be computed:

$$\theta_4 = \arctan 2(x_y, x_x) \tag{9.22}$$

Which can also be written on the following form:

$$\theta_4 = \arctan(\frac{x_y}{x_x} \tag{9.23}$$

With that being the final step in solving the inverse kinematics it is found that there is eight different solutions for the UR5 all denoting different combinations of the shoulder being left or right, the elbow being up or down and the wrist position.

9.2 Trajectory Generation

Trajectory generation refers to the development of a "time history of position, velocity and acceleration for each degree of freedom. The importance for this arises due to the need of having methods which compute a trajectory in multidimensional space while moving the robot from the start position, given by the tool frame $T_{initial}$ to end position given by the tool frame T_{final} while dealing with spatial and temporal motion constrains".[32] There are two methods of path generation:

- Joint space schemes: "path shapes in space and time are described in terms of functions of joint angles. This motion type is named Point-to-Point motion (PTP)". [32]

- Cartesian space schemes: ”path shapes in space and time are described in terms of functions of Cartesian coordinates. This motion type is named Continuous Path motion (CP)”.[32]

Joint space schemes: Using the point to point motion, a path was generated to describe the way the UR5 was working. The input used for the trajectory generation was obtained from the simulation developed in RoboDK and describes the movement of the UR5 from the conveyor belt to the Schenk de-balancing station and then to the Nolek leakage test machine. This are the coordinates of the initial and the final point:

$$\vec{\theta_o} = \begin{bmatrix} 587,331 \\ -169.879 \\ 339.554 \end{bmatrix} \vec{\theta_f} = \begin{bmatrix} -684,693 \\ 462,905 \\ 375,941 \end{bmatrix} \tag{9.24}$$

In the joint space scheme, knowing the time required to execute the movement and the initial and final θ, the trajectory the robot will follow can be calculated. In order to do that, a number of via points which describe the path of the UR5 are set, this is done because when computing only the final position in respect to the starting one, the trajectory generated won't correspond to the trajectory followed in the workspace and therefore wont be accurate. With this parameters the coefficients for the 3rd order polynomial are obtained:

$$a_0 = \theta_0 \tag{9.25}$$

$$a_1 = \dot{\theta}_0 \tag{9.26}$$

$$a_2 = \frac{3}{t_f^2}(\theta_f - \theta_0) - \frac{2}{t_f}\dot{\theta}_0 - \frac{1}{t_f}\dot{\theta}_f \tag{9.27}$$

$$a_3 = -\frac{2}{t_f^3}(\theta_f - \theta_0) + \frac{1}{t_f^2}(\dot{\theta}_f + \dot{\theta}_0) \tag{9.28}$$

Where θ_0 corresponds to the angle of the joint in the initial position and θ_f to the final one. In the same way, $\dot{\theta}_0$ corresponds to the initial velocity of the joint in the starting point and $\dot{\theta}_f$ the velocity in the ending one. The symbol t_f represents the time it takes the manipulator to go to one point to another. The coefficients showed above correspond to the ones in the following equation; $\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$.

In the start point, the initial velocity is equal to 0 because the manipulator is in a resting position, the same happens in the via points where the UR5 stops or at the end point where the simulation finishes. On the other hand, those via points which are taken to generate an accurate trajectory but which don't imply the stop of the motion, the robot is in movement and therefore has a velocity which needs to be calculated. From the RoboDK simulation, the input obtained corresponds to the Cartesian location of the robot, the quaternions, and the joint angles position. Dividing the difference between the angle of one via point and the one which comes right before by the time it takes the robot to move from one to another, the velocity can be obtain the velocity at which it is traveling.

$$\dot{\theta} = \frac{\theta_i - \theta_{i-1}}{t} \tag{9.29}$$

The following table shows the equations obtained after the calculations and describes how the manipulator moves according to the joint space scheme from one via point to another:

	$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$	$\dot{\theta}(t) = a_1 + 2a_2 t + 3a_3 t^2$	$\ddot{\theta}(t) = 2a_2 + 6a_3 t$
to via1	$\theta(t) = 185 - 1.34t^2 - 0.27t^3$	$\dot{\theta}(t) = -2.68t - 0.81t^2$	$\ddot{\theta}(t) = -2.68 - 1.62t$
to via2	$\theta(t) = 180 - 0.69t^2 - 0.08t^3$	$\dot{\theta}(t) = -1.38t - 0.24t^2$	$\ddot{\theta}(t) = -1.38 - 0.48t$
to via3	$\theta(t) = 174.1 - 1.42t + 10.08t^2 - 1.13t^3$	$\dot{\theta}(t) = -1.42 + 20.16t - 3.39t^2$	$\ddot{\theta}(t) = 20.16 - 6.78t$
to via4	$\theta(t) = 268.44 + 21.1t - 10.96t^2 - 320.82t^3$	$\dot{\theta}(t) = 21.1 - 21.92t - 962.46t^2$	$\ddot{\theta}(t) = -21.92 - 1924.92t$
to via5	$\theta(t) = 260 - 2t + 2.32t^2 + 0.68t^3$	$\dot{\theta}(t) = -2 + 4.64t + 2.04t^2$	$\ddot{\theta}(t) = 4.64 + 4.08t$
to Via6	$\theta(t) = 268.44 - 0.95t^2 + 3.89t^3$	$\dot{\theta}(t) = -1.9 + 11.67t^2$	$\ddot{\theta}(t) = -1.9 + 23.34t$
to Via7	$\theta(t) = 260 - 2t + 1.86t^2 + 0.22t^3$	$\dot{\theta}(t) = -2 + 3.72t + 0.66t^2$	$\ddot{\theta}(t) = 3.72 - 1.32t$
to via8	$\theta(t) = 268.44 - 1.97t - 30.41t^2 + 121.04t^3$	$\dot{\theta}(t) = -1.97 - 60.82t + 363.12t^2$	$\ddot{\theta}(t) = -60.82 + 726.24t$
to via9	$\theta(t) = 5.9 - 62.21t + 34.63t^2 - 4.82t^3$	$\dot{\theta}(t) = -62.21 + 69.26t + 14.46t^2$	$\ddot{\theta}(t) = 69.26 - 28.92t$
to end	$\theta(t) = 5.73 - 0.05t - 0.05t^2 + 0.05t^3$	$\dot{\theta}(t) = -0.05 - 0.10t + 0.15t^2$	$\ddot{\theta}(t) = -0.10 + 0.30t$

Figure 9.6: Table of equations

Cartesian space schemes: For further analysis on the trajectory, a Cartesian space scheme was developed to contrast the different paths of the manipulator depending on the method of trajectory generation. According to the Cartesian space scheme, with the affine matrix from the start to the end point the trajectory of the manipulator can be find by interpolation using the equivalent angle axis.

An affine matrix is a matrix such as the one showed below:

$$T_1^{Base} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & X_1 \\ a_{21} & a_{22} & a_{23} & Y_1 \\ a_{31} & a_{32} & a_{33} & Z_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9.30}$$

It consist of a transformation matrix A, which represents how the coordinate system of the $joint_i$ has changed in reference to $joint_{i-1}$.

And a translation vector which indicates the position in which $joint_i$ is in the space in comparison to $joint_{i-1}$. The problem is that translation is not a linear transform, and therefore, a 4^{th} component must be added, the w coordinate. This extra coordinate must serve only to the purpose of allowing the use of the affine matrix, but it shouldn't alter the final product, therefore, the w component must result in a new vector which has homogenous coordinates and the standard way to do this is by setting the w coordinate to the value 1.

By doing this, the translation vector obtained is in R^i but a matrix in R^{i-1} and therefore the affine matrix cannot be computed. To solve it, a new transformation matrix with homogeneous coordinates must be created. The standard way to do that is by adding an extra last row filled with 0.

From the RoboDK simulation, the input obtained corresponds to the Cartesian location of the robot, the quaternions, and the joint angles position. The Cartesian location of the robot corresponds to the translation vector. But for the transformation matrix, some further calculations were required. According to J.J.Craig in section 2.91 [33], using the following formula dependent on the quaternions (which are represented with the letter epsilon ϵ), the transformation matrix can be computed.

$$\begin{bmatrix} 1-2(\epsilon_2)^2-2(\epsilon_3)^2 & 2\epsilon_1\epsilon_2-2\epsilon_3\epsilon_4 & 2\epsilon_1\epsilon_3+2\epsilon_2\epsilon_4 \\ 2\epsilon_1\epsilon_2+2\epsilon_3\epsilon_4 & 1-2(\epsilon_1)^2-2(\epsilon_3)^2 & 2\epsilon_2\epsilon_3-2\epsilon_1\epsilon_4 \\ 2\epsilon_1\epsilon_3-2\epsilon_2\epsilon_4 & 2\epsilon_2\epsilon_3+2\epsilon_1\epsilon_4 & 1-2(\epsilon_1)^2-2(\epsilon_2)^2 \end{bmatrix} \tag{9.31}$$

With this input, the different affine matrices from each via point can be calculated, which results in several different matrices which represent the transformation of the manipulator at $Point_i$ relative to the base.

In order to interpolate using the equivalent angle-axis, the transformation required is the one from the start to the end point. Which can be obtained as followed:

$$T_{end}^{start} = (T_{start}^{base})^{-1}(T_1^{base})(T_1^{base})^{-1}(T_2^{base})(T_2^{base})^{-1}(T_3^{base})(T_3^{base})^{-1}(T_4^{base})(T_4^{base})^{-1}$$
$$(T_5^{base})(T_5^{base})^{-1}(T_6^{base})(T_6^{base})^{-1}(T_7^{base})(T_7^{base})^{-1}(T_8^{base})(T_8^{base})^{-1}(T_9^{base})$$
$$(T_9^{base})^{-1}(T_{end}^{base})$$

The result of this matrix is:

$$T_{end}^{start} = \begin{bmatrix} -0.9661055283 & 0.2014201391 & 0.1614683556 & -368.411371 \\ 0.1721682307 & 0.036652682 & 0.9843870979 & 1438.051071 \\ 0.1923677877 & 0.9788239172 & -0.0702708795 & 114.5212315 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9.32}$$

The next step is to interpolate this matrix, to do so the values of the angle and the vector K should be computed.

$$\theta = \arccos(\frac{a_{11}+a_{22}+a_{33}-1}{2}) \tag{9.33}$$

The value of the angle is $\theta = 179.05$

$$\vec{K} = \frac{1}{2\sin\theta}\begin{bmatrix} a_{32} & -a_{23} \\ a_{13} & -a_{31} \\ a_{21} & -a_{12} \end{bmatrix} \tag{9.34}$$

$$K_x = -0.1677691474$$
$$K_y = -0.9318358792$$
$$K_z = -0.882151416$$

When the matrix bellow is filled with the input of the angle and the components of the vector $\vec{K}$ (K_x, K_y, K_z), the next step is to proceed with the interpolation. For the translation vector it is used the same one as in the Transformation homogeneous matrix. 9.32

$$\begin{bmatrix} k_x k_x(1-\cos\theta(t))+\cos\theta(t) & k_x k_y(1-\cos\theta(t))-k_z\sin\theta(t) & k_x k_z(1-\cos\theta(t))+k_y\sin\theta(t) & x(t) \\ k_x k_y(1-\cos\theta(t))+k_z\sin\theta(t) & k_y k_y(1-\cos\theta(t))+\cos\theta(t) & k_y k_z(1-\cos\theta(t))-k_x\sin\theta(t) & y(t) \\ k_x k_z(1-\cos\theta(t))-k_y\sin\theta(t) & k_y k_z(1-\cos\theta(t))+k_x\sin\theta(t)) & k_z k_z(1-\cos\theta(t))+\cos\theta(t) & z(t) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9.35}$$

The following matrix represents the trajectory of the manipulator when moving from the start to the end position through all the via points analyzed from the Cartesian space scheme.

$$\begin{bmatrix} -1.056151649 & 0.3272710873 & 0.2805255227 & -368.411371 \\ 0.2980191789) & -2.736379401 & 1.64670928 & 1438.051071 \\ 0.3114249548 & 1.641146099 & -2.556137819 & 114.5212315 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9.36}$$

9.2.1 TCP

TCP stands for Tool Center Point and is an expression used when dealing with the Tool Coordinate System. This system formulates a way of reference for describing a moving points position in a Cartesian space, it is among other used when dealing with programming of automated robotic systems. In this case the chosen center point and sometimes an angle of a tool is used to define machine movement, as seen in numeric controlled machines.[34]

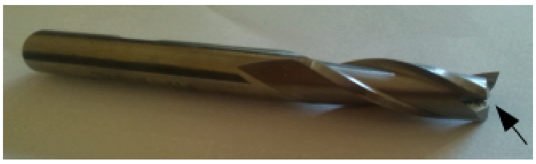

Figure 9.7: Cursor points to the typical placement of TCP, at the tip and in the center.

TCPs are found in two types: movable or stationary

Moving TCP: Most applications are moving TCP, i.e. a point that moves through space. An example could be the tip of a drill as seen in figure 9.7.

Stationary TCP: Not as often in applications a stationary TCP are being used. In this case the TCP are defined in context to the stationary equipment. An example could be the arc tip of a welding gun.

In the case of the projects gripper the TCP is placed in the dead center, meaning in the center of the arc when the gripper is closed, and in the middle of the tool. The reason for the chosen stationary TCP being the sake of an reference point and that the gripper grips around the rotors centerline.

9.3 CAD Modeling

Computer aided design (CAD) can be described as usage of the computer systems in assistance with creating, adjusting and modifying the design. Usually specific software is used for such purposes. In our case, CAD models were made in software provided by Aalborg University (licensing) called SOLIDWORKS®.

9.3.1 Rotor

As the main part that needs to be transported and with which testing needs to be done – rotors were created as a CAD model in SOLIDWORKS®. This needed to be done for testing the workstation (e.g. creating simulation, off-line programming and etc.).

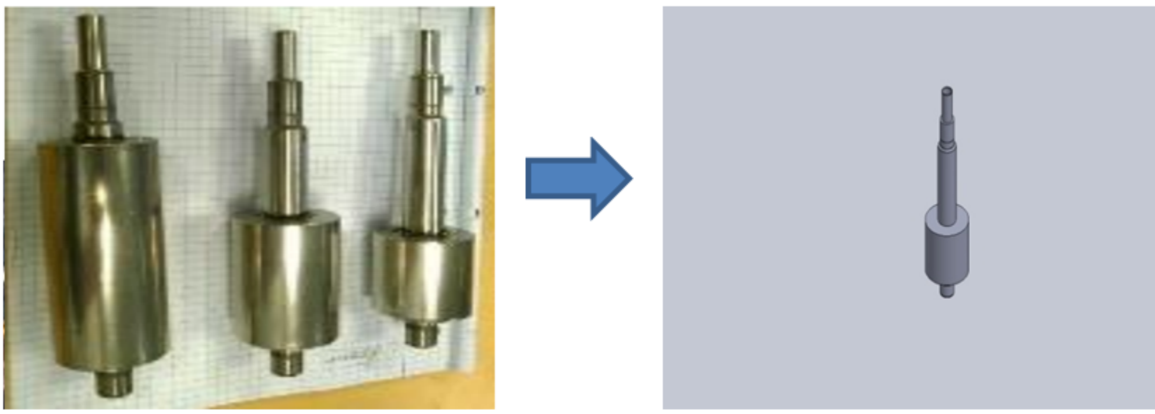

Figure 9.8: One of the rotors – Small rotor

Additionally proper gripper for transporting and placing the rotor was designed.

9.3.2 Gripper

To transport the rotors, it was needed to create a gripper that could match the measurements of the rotor (e.g. radius) and have a good practical use. Then using the measurements of the rotor, a prototype was developed.

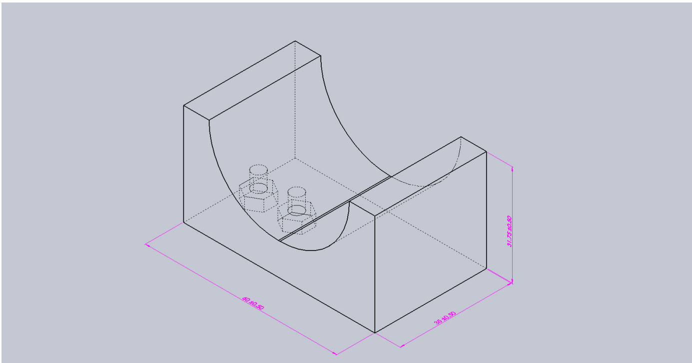

Figure 9.9: One half of the prototype gripper Rev1

Figure 9.9 shows a 3D-sketch of one half of the gripper with M4 nut holes to mount on the RG2 tool. After the creation of the sketch, the gripper was printed and tested. The design of the prototype is developed from the thesis, that it should be able to hold the rotor without dropping it. In the development phase the focus was not on making a slim gripper, but the functionality of it, therefore it has a box form. When testing out the gripper it was clear that the rotor could not go through the opening due to width restrictions on the tool and therefore minor tweaks were made as seen in figure 9.10

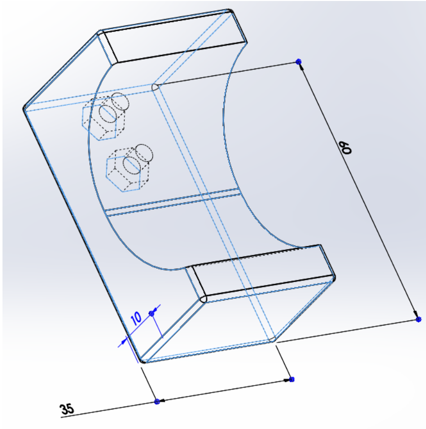

Figure 9.10: One half of the prototype gripper Rev2

9.3.3 Other Parts

Additional details have been created for the simulation of the workstation, such as the representation of parts from Schenk (to the left), Nolek (at the top) and engraving station (to the right) where rotor is supposed to be placed.

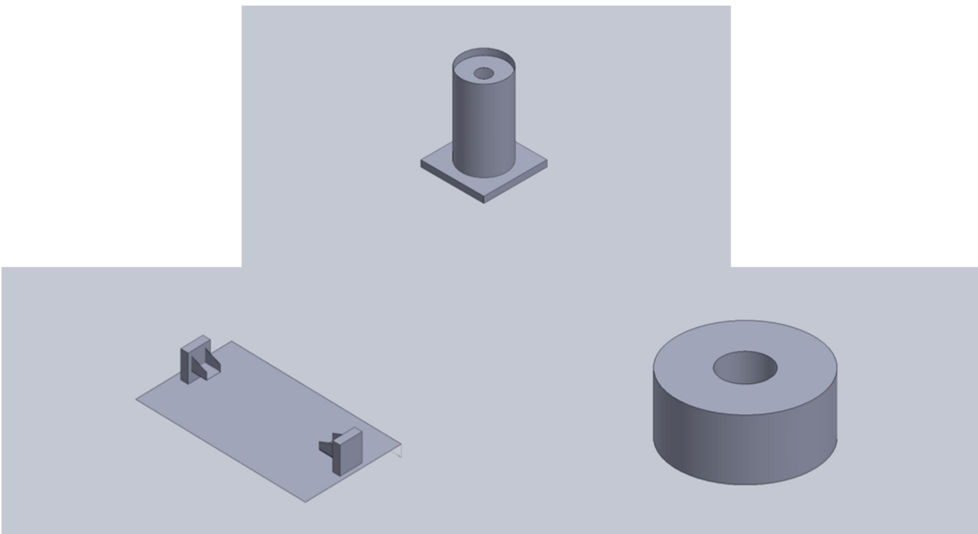

Figure 9.11: CAD models of machinery stations

The parts seen in figure9.11 were needed for the implementation in the workstation simulation. They were approximately optimized to fit a rotor in them, so that the off-line testing could be done. In the end the workstation for simulation can be seen in figure 9.12:

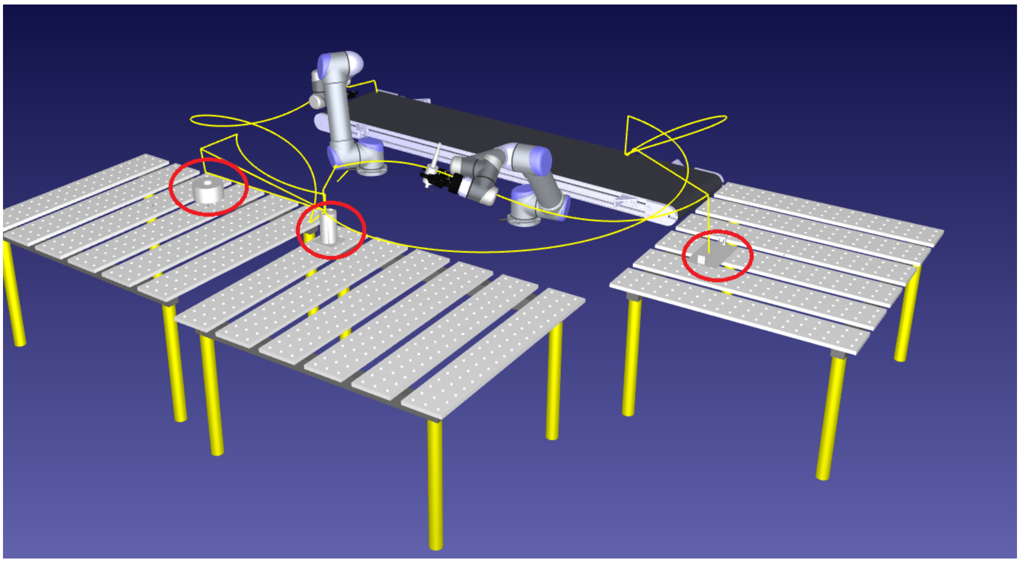

Figure 9.12: CAD models in the workstation

9.4 Simulation

Seeing as the task on hand involves heavy machinery and is situated in Bjerringbo, Denmark, it is not possible to do on-line programming. Therefore an off-line approach was taken, in order to do this, the simulation tool "RoboDK" was used, seeing as this is the tool that Universal Robots recommends, as well as the fact that the RoboDK supports Universal Robots models. Should another tool have been used, the simulations would have been done using ABB or other manufactures robots.

9.4.1 RoboDK

The RoboDK is an simulation tool, to program the industrial manipulators away from the production line (off-line programming). This approach to programming of the manipulators is favorable by larger companies, who relies on a continuously running production.

The RoboDK excels in simulation of the manipulators, as they have an online library, containing most of the manipulators as well as several objects for the simulation purposes (e.g. a conveyor belt). It is an easy to learn development platform, where the user can either get work with off-line programming or use the built in tools for the drag and drop programming. The latter approach seems very similar to the way the UR is programmed on-line as seen in the figure 9.13.

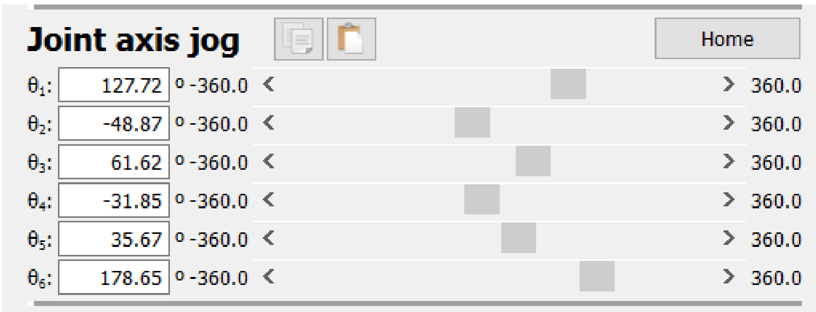

Figure 9.13: Sliders for moving the different joints

When the programmer has reached the desired position of the joints, the programmer can press on a button and that waypoint was saved for future use. When all the desired waypoints have been created, the programmer creates a program for adding the movements between waypoints. This is done by selecting the program wanted to add a command to and then selecting the desired type of movement (linear or joint), besides this, the program also allows for several other commands, such as using own code.

The RoboDK also allows the programmer to choose a program and then export it for the selected manipulator. In this particular case, the RoboDK would give the programmer a python script to execute use of the teach pendant, if desired.

9.4.2 The Program

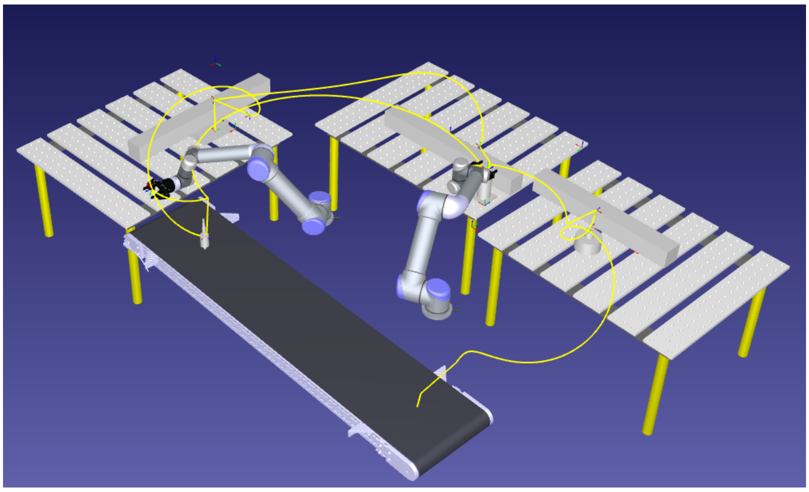

Figure 9.14: An overview of the station

The workstation as seen in the figure 9.14 was created by assembling different CAD models such as the conveyor belt, tables for recreating the workstation and parts from the Schenk, Nolek and the engraving station to place the rotor in. The simulation itself was created from the information obtained from Grundfos (pictures, videos and etc.). Approximate positions were included in the simulation.

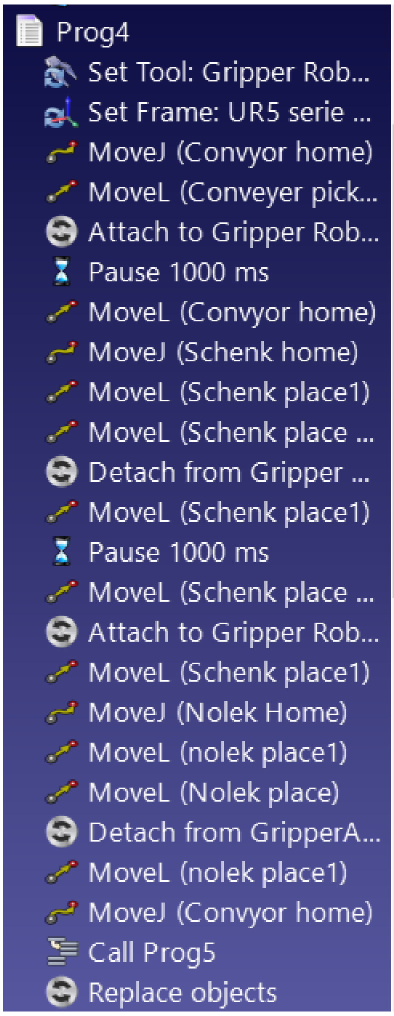

Figure 9.15: The RoboDK program for UR5 A

In figure 9.15 the content of an off-line program in RoboDK can be seen. It consists of things such as the joint movements, linear movements, pauses in order to make sure the gripper grabs the rotor, attaching and detaching. This program was specifically created for the simulation of the workstation.

```
movej([1.441991, -1.544965, 1.235868, -1.339017, 4.738220, 3.038618],accel_radss,speed_rads,0,blend_radius_m)
movel([1.387375, -0.756426, 0.439542, -1.529626, 4.856255, 4.685230],accel_mss,speed_ms,0,blend_radius_m)
movel([1.381952, -0.573341, 0.651008, -1.788439, 4.798783, 4.537856],accel_mss,speed_ms,0,blend_radius_m)
set_digital_out(8,False)
sleep(1.000)
movel([1.387375, -0.756426, 0.439542, -1.529626, 4.856255, 4.685230],accel_mss,speed_ms,0,blend_radius_m)
sleep(1.0000)
movel([1.381952, -0.573341, 0.651008, -1.788439, 4.798783, 4.537856],accel_mss,speed_ms,0,blend_radius_m)
set_digital_out(8,True)
sleep(1.000)
movel([1.387375, -0.756426, 0.439542, -1.529626, 4.856255, 4.685230],accel_mss,speed_ms,0,blend_radius_m)
```

Figure 9.16: Snippet for Schenk

In the figure 9.16, one can see the part of the program responsible for moving the rotor from the conveyor to the Schenk. This part of the program consists of two moveJ commands, for the large-range movements and several moveL commands to place and pick the rotor to and from the Schenk. set_digital_out controls the gripper, where True will make it grasp together and vice-versa with False. Lastly the program has several delays, which are set to one second in order to make sure the gripper gets a hold of the rotor before moving again.

First of all, the rotor is picked-up by the manipulator and then moved to the Schenk from the conveyor belt, as seen in the figure9.17:

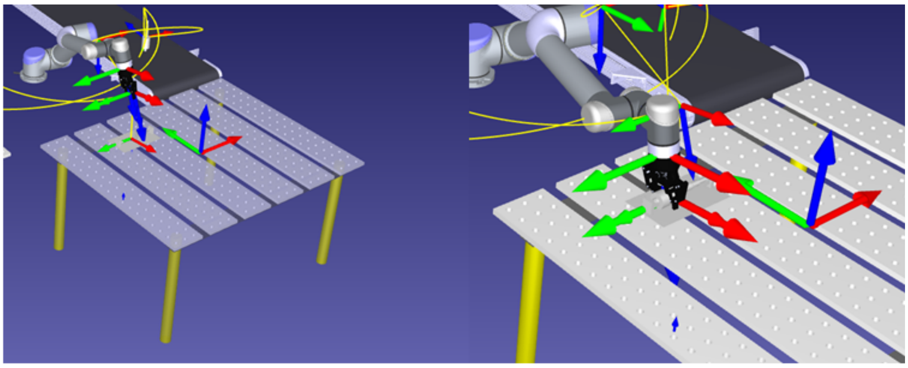

Figure 9.17: Rotor placement in Schenk

From the Schenk, the rotor is picked up and transferred to the Nolek as seen in the figure 9.18:

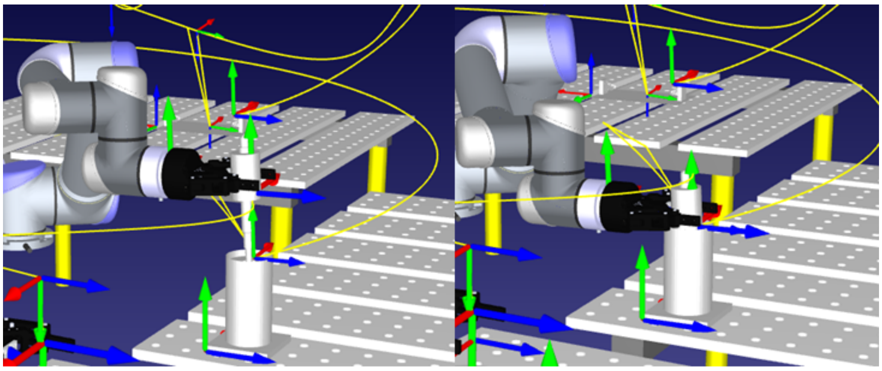

Figure 9.18: Snippet for rotor placement in Nolek

Afterwards it is relocated to the engraving station and finally placed back to the conveyor belt (to create a loop for simulation purposes), as shown in the figure 9.19:

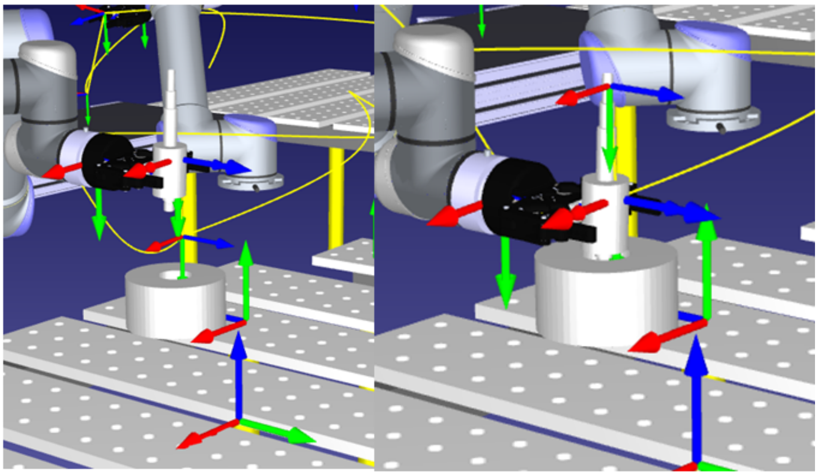

Figure 9.19: Snippet for rotor placement in Engraving Station

Though the rotor is supposed to go to the palletizing at the factory line, in the simulation it was chosen to go back to the conveyor in order to ease the group of non-important scripting (spawning a new rotor in the place of the other one). In general the simulation can be improved by adding the full stations, instead of placing parts from the stations, where rotor is placed(can be seen in figure 9.14 that station is not fully built, just built in a functional way). Another additional improvement would be adding pallets and multiple rotors, to see if the simulation can handle everything correctly. The simulation was done by using two UR5 manipulators, which is not fully optimal solution (most optimal would be to use one manipulator, but the reach of the UR5 is not adequate), because they can collide with each other and the workstation (since their workspaces coincide), which can be seen in the figure 9.20

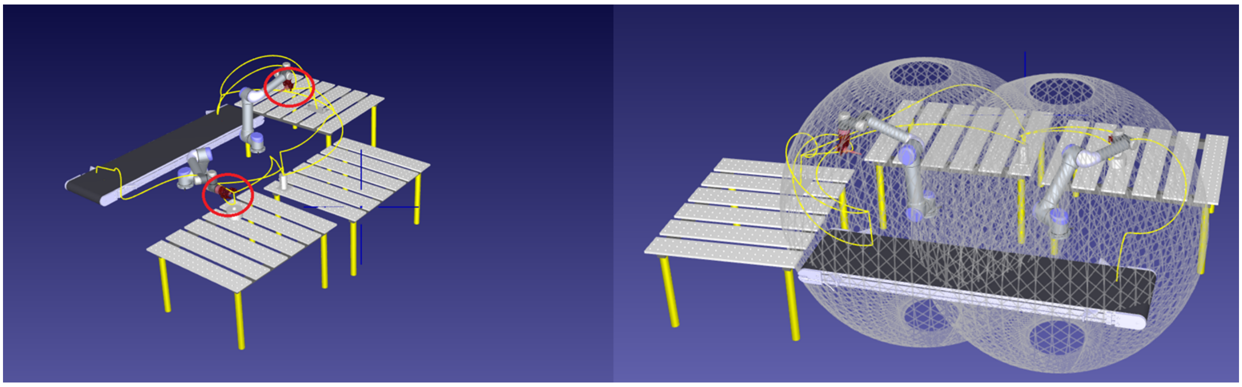

Figure 9.20: Demonstration of a potential collision

9.5 Risk Assessment

A risk assessment is the identification evaluation and estimation of the levels of risks involved in the situation [35]. The risk assessment scope according to ISO standard EN 12100 is to help designers when designing machinery to identify and reduce risks. The risk assessment is supposed to involve the risk analysis, the risk evaluation, and a risk reduction Risk analysis includes the determination of the limits of the machinery, hazard identification and risk estimation.[18]

Determination of the limits of the machinery: Its purpose is to define, the different modes the machine can operate under, along with different intervention procedures, meaning what action the users should perform, should a malfunction occur. It should also analyze foreseeable misuse and include the anticipated level of training for any person using the machine. This should take into account possible exposure to hazards associated with the machinery based on experience level, whether it be little or a lot of experience. The space or time limits is considered and other limitations not mentioned above.[18]

Hazard identification: When the limits of the machinery have been determined, it is necessary to assess the potential hazards through all phases of the machines lifetime. This must look at all human interaction with the machine, along with that it is necessary to look at the machine when it is operating, as expected and during a potential malfunction. It is also necessary to look at when the operator is using the machine as intended or if the machine is misused.[18]

Risk estimation For each hazardous situation identified in the hazard identification, there should be estimated the elements of risk, this is used to determine how expansive the damage are, along with the potential to reduce the likelihood of these occurring. The elements of risk involves severity of risk, the probability of occurrence of that harm along with the technical and human possibilities to reduce the risk of harm. The risk estimation defines what parts are sent forward to the risk reduction.[18]

Risk reduction: Risk reduction is setup up in three steps. Inherently safe design measures, safeguarding and or complementary protective measures, information of use. These three steps is used to reduce two main elements:

- Severity of the harm.
- Probability of the harm occurring

This is a brief explanation of the risk assessment, in the following section the standards is presented before the actual risk assessment was made.[18]

9.5.1 Standards

Standards are a set of guidelines or rules that tries to ensure repeatabillity and validity. An example could be the metric system, which ensures a meter is meter anywhere, and provides guidelines for how to measure a meter. [18]

In this project given its nature, locations, and actors, the standards described in DS/EN ISO 12100, from Danish Standards, was used for the risk assessment. This is an international collection of standards, covering both Europe and Denmark. The standards are for safety of machinery, general principles for design, risk assessment and risk reduction. ISO (the International Organization for Standardization) is a federation of members, such as international organizations, either governmental or non-governmental. The main intent of this standard is to give a framework and guidelines for implementing safety regarding machinery.[18]

These standards are divided in different categories, being:

- ”Type-A standards (basic safety standards) giving basic concepts, principles for design and general aspects that can be applied to machinery.”[18]

- ”Type-B standards (generic safety standards) dealing with one safety aspect or one type of safeguard that can be used across a wide range of machinery.”[18]

- ”Type-B1 standards on particular safety aspects (for example, safety distances, surface temperature, noise).”[18]

- ”Type-B2 standards on safeguards (for examples, two-hand controls, interlocking devices, pressure- sensitive devises, guards).”[18]

- ”Type-C standards (machine safety standards) dealing with detailed safety requirements for particular machine or group for machines.”[18]

9.5.2 Risk assessment of the Prototype

Determination of the limits of machinery

The modes of the UR5s: The prototype consists of two UR5 manipulators working in a certain area. The manipulator have two operating modes, fully running, and emergency stop. if any malfunctions should happen there is an emergency stop button, this will seize all operation and stop the machine. When a full stop is engaged, the power is terminated and any human in any risk of harm can be helped away from the machines. Any intervention done should be during a full emergency stop. The UR5 can be programmed to slow down operation when in proximity to a human, this allows for safer cooperation between the UR5 and the Human[36].

Time limits: The minimum life expectancy of the UR5 is 35000 hours according to Universal robots [36]. This means that a check of the status of manipulator must be done at least every 35000 hours. However smaller checks should be done at a more frequent rate.

Expected level of experience: The expected experience level is that the operator have experienced working in a factory but do not necessarily know about the manipulator and its technical specifications, however it is expected that the operator is informed about safe handling of the manipulator. The technician is expected to have technical knowledge about the UR5 along with knowledge pertaining to safe operation with the manipulator.

Exposure of other personnel: Since the workstation is location is placed deep within the closed off factory, the risk of unassociated personnel accessing the workstation is little. However, there should be safety warnings in clear sight near the manipulator to ensure easy access to information to avoid potential harm.

The space limits: Since there are two manipulators, the space for any operator is limited. While the goal of the robot is to work alongside humans to fit the requirements there is a need to have two manipulators working alongside each other. This means that the human must work within limited space, for objectives such as quality control. However, the robots can be programmed to slow down when a human gets into the proximity of the robots work area . This would allow human workers to get closer to the robot while still not putting them in risk of harm. The dimension of the workstation with the two manipulators is so there is 70 cm of free space between the manipulators at all times, as shown in the figure of the simulation. This means that while a human operator can stand in between them, the movements done can only be at a minimum since an movement error on the operators side, could lead to a collision.

Hazard identification: During the creation and development of the UR5, this group is not involved since the costumer will buy this manipulator. However when Grundfos will install the machine it is necessary to have a risk assessment on the manipulator itself in corporation with the machine and any other technology added during this project (primarily the gripper as seen in figure 9.21), it is also necessary to analyze the programming and how the manipulator is used.

Possible states of the machine: A risk with the UR5 is the fact of how it handles the rotors to and from the different workstations. Currently the manipulators hold the rotor horizontally (as seen in the following figure 9.14). This have some safety risk in that the tips are both pointed outward so if a worker is hit by the gripper, the rotor is the first thing to impact negating the UR5's safety feature.

The gripper is made from ABS, which is a strong plastic[37], however since there are laser engraving there might be a risk of the material melting due to high temperature, either the gripper itself or the non-slip surface which have a lower tolerance to high temperature. This might negatively affect the performance of the gripper leading to higher risk of harm. This could most likely be averted by the use of stronger materials.

The gripper have the risk of dropping the rotor. The gripper was attached with four screws

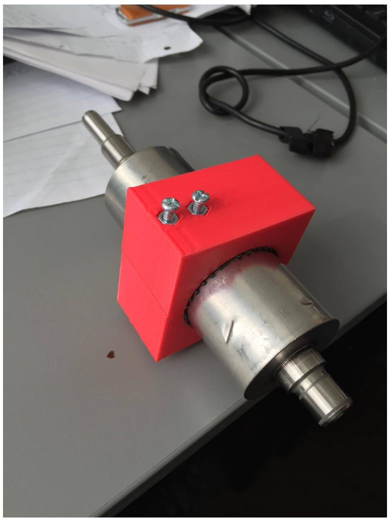

Figure 9.21: Gripper holding Rotor

and the gripper itself is gripping only using the non-slip surface, meaning if any of these fails during operation, the gripper could throw the rotor potentially leading to harm to personnel.

During testing, the gripper was checked for whether the rotor would slip while the gripper were holding it. While it did not let go of the rotor once it held the rotor, there seem to be a high margin of error and the precision have to be very precise for the gripper to handle the rotor properly.

Since the gripper is made from plastic there is the potential risk of it shattering, meaning the potential of shrapnel that could have a risk of harming personnel. This could be another factor that might mean that another material for the gripper should be used. The two manipulators are working in close proximity to each other, this could lead to accidents if the timing on one manipulator is off, it might lead to a collision. The use of two manipulators have these risks involved.

- Any emergency stop needed on one manipulator must be on both manipulators to avoid collision.
- The timing of both manipulators must be correct to avoid potential collision between the UR5
- The space for the operators to move on is decreased so the operator must know the

movements of the robot

It were also discussed to have the UR5 positioned on a moving XY-axis so that one UR5 could reach all stations. However since the station will have to have an operator working along side the manipulator(s) this is not a suitable solution, since the manipulator would have a high risk of hitting the user and the area surrounding the manipulator would not be safe.

Risk estimation: During the risk estimation the main focus was on the gripper and the changes made directly to the manipulator and the environment. The risks looked at in the risk estimation was estimated whether these should be taken further for risk reduction. The risk looked at in the risk estimation are:

- The grippers handling of the rotor.
- The material the gripper is made from.
- The potential of the gripper shattering.
- The manipulator dropping the rotor.
- The potential of the gripper melting.
- The Space between the manipulators.

These are the risks that was estimated in the risk estimation, the probability of the risk happening, along with the severity of potential harm was taken into account, before it was chosen whether the risk of injury is great enough that there needs to be made risk reduction on the given risk.

The grippers handling of the rotor:

Since the gripper handles the rotor horizontally, it is needed to calculate what force the rotor would hit an operator with. This was done assuming the top speed of the UR5 along with the smallest impact area (meaning the smallest circle in the end of the rotor). In order to be sure that none of the rotors will create too critical of an impact. The calculations was made using the largest rotor. The largest rotor weighs 1.1 kg and the robot moves at a maximum of

1 m/s, the area of the smallest circle on the rotor have a diameter of 0.6 cm. This allows us to calculate the force of the impact between operator and the rotor

$$F = \frac{(1.1kg \cdot 1m/s)}{0.5s} = 2.2N \tag{9.37}$$

This is the force of the rotor hitting a person, but the impact of the smallest area of the rotor needs to be known to find what amount of pressure this would actually hit the person with.

$$A = \pi \cdot 0.003^2 m = 0.00002m^2 \tag{9.38}$$

to calculate the pressure the rotor will induce if it where to hit a person with the smallest circle.

$$P = \frac{F}{A} = \frac{2.2N}{0.00002826m^2} = 77848.55Pa \tag{9.39}$$

This could cause severe harm to a person depending on where the rotor hits. Since the rotor is mostly hollow in the smaller circle, the amount of pressure could be even greater.

Probability of occurrence of harm: Since this have not been implemented physically in a workstation, the way this was estimated is based on the time the operator spends in reach of the manipulator, and the probability the manipulator have of impacting the operator.

Since this workstation will have to have an active operator working alongside the manipulator, the operator is within the workstation along with the manipulator. This means that the potential for the operator being struck by the manipulator is there, since the operator is in reach of the manipulator. This leads to the conclusion that, this have the potential of harming a individual along with a high enough probability that this could happen, this should be taken forward to the risk reduction.

The Material the gripper is made from: The gripper is made from ABS that is structurally sound until 90 degrees Celsius [37]. This should mean that the probability of this melting is low even with the laser engraving station. However the non-slip surface, and the glue holding it onto the gripper could be an issue. The strength of ABS is high[37], meaning the risk of the material shattering is low as well. Both of these could be very severe if an accidents were to happen but the probability of it happening is low. Therefore this will not be taken towards risk reduction, however it does not mean that the gripper will stay the same, due to other risks involved.

The space between the manipulators: In the previous sections the space between the manipulators were mentioned to be 70 cm. This is believed to be enough for a human to occupy, though there would be risk of harm, if the operator works inside the station. The inherent issue with using the UR5 is that the UR5 cannot by itself reach all the stations. This would mean that the space for the manipulator to maneuver on is limited. Different options were discussed to more optimally allow space in the workstation and reduce risk of impact. one of the solutions would be to arrange a single UR5 on a moving platform to allow it to move to reach all the stations. This would however not be safe since it would not allow the worker to work in the workstation safety due to the increased chance of collision. another potential solution would be to use the bigger UR10 that have a bigger reach. This is suitable but cannot be implemented during this prototype. This will not be taken further to risk reduction, due to this issue, will not be present, in the final product.

Risk reduction: The things estimated to be in need of risk reduction is to be analyzed based on a three step system inherently safe design measures, safeguarding and/complimentary protective measures and information for use. These was implemented for the risks analyzed in the risk reduction.

The grippers handling of the rotor: As mentioned in the previous section the problem with the gripper is that it holds the gripper horizontally, this have the potential of the gripper hitting the operator, or dropping the rotor impacting the operator, which could cause severe damage. This was looked at to see if there is a potential for redesigning the gripper or putting up safeguarding reducing or eliminating the risk.

Inherently safe design measures: The design of the rotor is meant to be simple, for the prototype. In the finished product the gripper will have to be redesigned. This could be a three fingered gripper allowing for more optimal gripping but also minimize the change of the gripper dropping or impacting an operator at one of the smaller surfaces. The gripper would also need to be made from different materials, such as aluminum allowing for strength and a higher melting point. For the prototype holding the gripper vertically would make sure that should an impact occur, the biggest part of the rotor will be the one impacting reducing the risk of damage drastically.

Safe guarding and complimentary protective measures: Since the purpose of this prototype is to have an operator working alongside a manipulator within a workstation, having fencing and other safeguarding materials, should be, if possible, avoided.

Information of use: Before an operator works within the workstation, he should be properly informed about the things to be wary of, and what to avoid. There should be informational stickers hung up in clear sight to clearly indicate where the manipulator can reach and what to do during all potentially dangerous situations.

It is believed that these actions would reduce the risk, to a place where both the potential severity of harm and the probability of this occurring is negligible.

10 Testing

The testing is being done in a controlled environment. The tests are being documented through taking pictures, along with videos when relevant. All the tests conducted are based on the Acceptance criteria. Some of the product requirements were not phrased ideally and the tests were not as effective, as they could have been. The safety requirements could have been phrased in form of impact calculations making it easier to test, and get concrete numbers to compare with, instead of ineffective results. The CO_2 emission was only tested based on calculations, and therefore was not an appropriate requirements, since it was not inherently testable. The flexible and legality requirements is not something that can be tested, only checked up on through research, making it more appropriate to conclude on, in the problem analysis.

Acceptance test specifications			
Requirements	Criteria	How to Test	Pass/fail
TCP/IP	Able to connect to the internet.	Check for TCP/IP capabilities on the manipulator.	”Pass”
Payload	Able to lift the heaviest of the rotors, weighing 1,1 kg.	Have it lift the heaviest rotor.	1100gram
Range – Conveyor	Able to reach the Conveyor belt with the incoming rotors.	Measuring the distance the manipulator can reach.	850mm
Range – De-balancing station	Able to reach the de-balancing station.	Measuring the distance the manipulator can reach.	850mm
Range – Leak station	Able to reach the leak station.	Measuring the distance the manipulator can reach.	850mm
Range – Engraving station	Able to reach the engraving station.	Measuring the distance the manipulator can reach.	850mm
Output	Able to produce 40 units per hour.	Time how fast it takes for one work cycle and scale it up to one hour.	51 units
Safety	Unable to harm a person.	Test impact force.	”Pass”
Fencing	Able to work without a safety fence round it.	Check if the there is a stop function	”Pass”
Low repetition	Must not require workers to perform repetitive work in order to function.	Time if one work cycle takes longer than 30 seconds.	77.63sec
CO_2 emission	Must not exceed more than a third of what an average person emits per year.	Through Calculation an estimate is made.	0.351276 metric tons
Uncertified labor	Must not have any involvement with uncertified labor.	Check if the manufacturer uses uncertified labor.	”Pass”
Flexible	Able to install and setup within 3 hours.	Research information from manufacturer	>1 hour
Legality	Follows standards.	Check if it follows relevant standards	”Pass”

Able to lift the heaviest rotor:

The UR5 have a carrying capacity of 5 kg. However to test the carrying capacity, the UR5 was made to lift the heaviest rotor which weighs 1.1 kg. This was a success. The manipulator were capable of lifting the rotor and moving with it effortlessly. as shown in figure 10.1

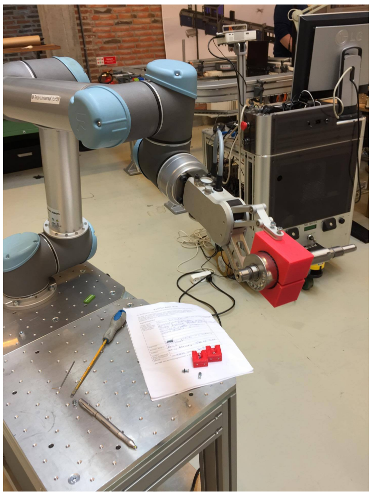

Figure 10.1: The UR5 holding the rotor

Though the range requirements have not been tested on-line, due to the lack of the actual work station, it is our belief that using one UR5, all stations can not be reached. These hypothesis have been tested with the simulation, which shows that the first UR can reach the first three range requirements, whereas the second manipulator can reach the rest.

Able to produce 40 units per hour

The cycle time of 10 units is measured, since the first time will not have the full cycle the first was discarded, the remaining 9 was calculated on. This was done for the two programs on the one UR5 manipulator made available during this project. The two times are added together, and averaged to find the cycle time for a single unit. Based on this the amount of units produced per hour is calculated.

UR5 program 1:

$$\frac{(39.2s + 39.21s + 39.22s + 39.23s + 39.24s + 39.23s + 39.19s + 38.84s + 39.35s)}{9} = 39.19s \tag{10.1}$$

UR5 program 2:

$$\frac{(28.28s + 28.45s + 27.99s + 28.44s + 28.73s + 28.23s + 28.43s + 28.44s + 29.03s)}{9} = 28.44s \tag{10.2}$$

With the ten seconds from Nolek, the final cycle time for a single unit is :

$$39.19s + 28.44s + 10s = 77.63s \tag{10.3}$$

It is then converted to minutes and divided by 60.

$$\frac{1.1763min}{60min} = 51.0 \tag{10.4}$$

This means that the average amount of units the solution can produce during an hour is 51 units

Safety + fencing:

The safety of the UR5 was tested by having an individual standing in front of the manipulator while running to check the stop on impact safety system. along with having a individual press the emergency stop button. and see how fast it stops.

Due to the UR5 moving slowly, the manipulator could push a individual but not damage them. The emergency stop button worked, stopping immediately, when pushed. It can be seen that the UR5 is safe to work around and do not need fencing, this is also shown in standard DS/EN 12100:2010[18].

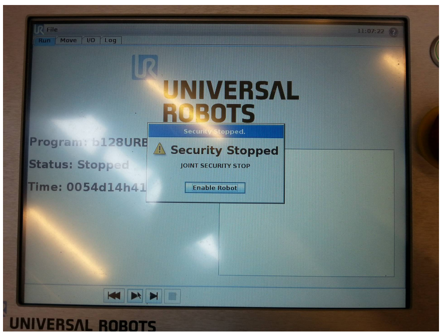

Figure 10.2: The Teach pendant showing there is an error

Seeing as the cycle time for one rotor going through the work station, was 77.63s, it can be concluded that the worker was doing low repetitive work.

To determine the carbon emission there are a few things that will have to be known, which is how much electricity the UR uses, and the average carbon emission per KWh used. The UR uses 200W[38] and the average carbon emissions per KWh in Denmark are 401 gram/KWh[39]. If assuming that the manipulator would be operating for 12 hours a day and do not include holidays, but assume that it is running every day, the yearly energy consumption can be calculated :

$$200W \cdot 12h \cdot 365 = 876000Wh \tag{10.5}$$

The yearly energy consumption is 876000 Wh, and to calculate the carbon emission it has to be changed to Kwh:

$$\frac{876000Wh}{1000} = 876Kwh \cdot 401\frac{gram}{Kwh} = 351276gram \tag{10.6}$$

So the estimated amount of carbon emissions produced during a year was, following the assumptions made about the UR operating time, 351276 gram or 0.351276 metric tons per year, with the average carbon emission per capita in Denmark is 7.2 metric tons our requirement about carbon emissions is passed[40].

The UR5 is according to videos[41], not own tests, by universal robots, fast and easy to setup and install due to the fact that it is low weight and easy to program. Some of that has to do with the user friendly graphical interface. Therefore the requirement about flexibility can be passed.

11 Further Development and Discussion

In the future the group will go into further development regarding the manipulator, and improve areas that are not within the groups skill set yet. This will correct some of the safety concerns within the workstation, and general handling of the rotors. These corrections will solve some of the delimitations, and problems that were decided not to include.

- The current system does not recognize if there are any defects on a rotor, and for future development a system that are able to recognize defects can be created. This makes the entire process in the workstation void, and the manipulator will just put the rotor in a pallet assigned for defective rotors. The system could either be laser or camera based, and would be mounted on the gripper or tool, in such a way that it will have a clear view. It could also be a system like the Danish return system for bottles, so every rotor that enters on the conveyor belt would be going through scanning system.[42] a model of this could be like in figure 11.1.

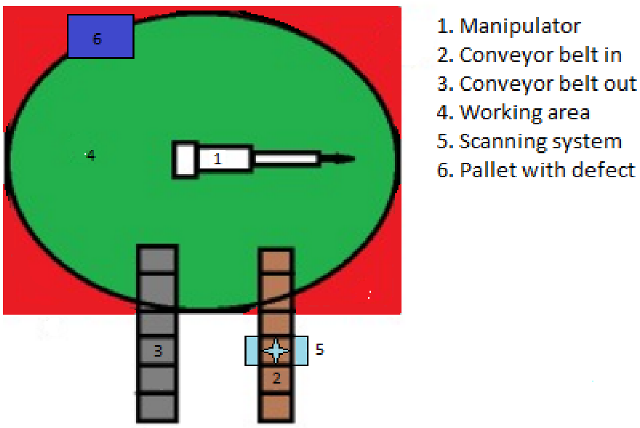

Figure 11.1: A safe workstation

- The gripper on the manipulator has no pressure sensors to know whether or not it is gripping on to something. This was one of the focuses to implement in the future, so the manipulator will not do a full cycle in the workstation without carrying a rotor. This will also ensure that the gripper does not use unnecessary force on the rotor, or anything else it would grip by mistake.

- Due to restrictions during the project there was only access to an UR 5 which has some limitations. To solve every task in the workstation a manipulator with greater reach is preferred. Since the UR10 have an extended, reach this would be a better choice. This would prevent the group from doing any changes to the workstation at the company, which is preferred.

- The prototype gripper is printed on a 3D-printer and is made out of plastic with non-slip material glued to it. An alternative to this could be a gripper made of metal tested for wear and tear to ensure longevity of the product. With proper flexible material at the grip for safe handling. The design will most likely not stay the same as it is too big to place the rotors on the designated pallet. A more expensive solution could be a gripper hand with 2-3 articulated fingers and adjustable grasping modes, this would also ensure the manipulator was more flexible and could be converted to a different task, such as giving the manipulator the ability to operate the machines.

- The stations have different indicator system to show when their respective job is done and at the moment the manipulator does not have any way of recognizing these indicators. In the future a system is developed, so the manipulator knows when a station is ready for rotor insertion and when completely ready for pick-up again. Furthermore the manipulator is able to start every station, so a worker does not have to be involved at all in these processes and thus reducing the risk for repetitive work and work related injuries.

- General movement of the manipulator is improved such as that the risk of harming a worker is lowered greatly. Movements such as in which position the rotors is held while moving, so no workers are accidentally hit by the pointy end of anything, and is designed so it is always a flat or broad side of an object towards areas where workers are involved.

- The group plans to do future testing whether or not it is possible to get the same result with just one manipulator. Without upgrading the manipulator. There is some experimentation in the workstation with the placement of the different stations, to get the most efficiency, while still making it accessible to a worker.
- Even though robots replacing human theme was mentioned before, it still remains a concern that people might lose job because of that. Even though they can be requalified or sent to another job. This question still concerns human ethics
- The current solution with the manipulator does not have any kind of quality control implemented, regarding the rotors. whether or not they have irregularities either before entering the workstation, or if anything is happening to the rotors within the workstation. The QC still needs to be done by a person on the floor, whom preferable should be replaced entirely by the manipulator
- As part of this project a UR5 was provided. However through the measurements of the UR5 is reach in comparison to the workstation, illustrated that the UR5 by itself could not reach all the stations. This meant that this prototype is based on two UR5 manipulators to ensure the appropriate reach. UR10 might have been used instead for testing.
- The workstation cannot be handled without a human operator, since most of the activation in the workstation is done manually. Even then, because of usage of UR5 reach, rearrangement of workstation might be needed.
- During the requirement specification a lot of the requirements were not phrased ideally, meaning that when it came to testing these, a lot of them were not as measurable as was first intended. This meant that the testing period was not as in depth as could have been desired. A lot of the reason for this was inexperience, this is the first project with requirements and a lot of these can be improved upon for future project. The testing was done in the end of the project period and the testing period had to be cut shorter due to lack of time in order to reach the deadline for the project. When looking at the tests conducted it is clear that for future projects of this kind, access to the specific workstation or a reproduction is needed for more accurate testing. In the future, testing would be done again to exclude possible errors.

- Most of the numbers for calculations were taken from simulation and not the actual real environment test. In the end calculations are mostly referred to the simulation and may cause small problems in the actual real-life calculations. Additionally, some misleading points happened during calculations, which lead to moderate loss of time.

12 Conclusion

The workstation entails three stations, the Schenk, Nolek and Engraving station, with a human operator, who moves the rotors around and performs quality checks. The Work is defined as repetitive if, the cycle time is more than 30 seconds. Due to the fact that the cycle time of the machines is 10-12 seconds, it can then be concluded that the work conducted in the workstation is high repetitive and must be reduced. To reduce repetitive work, a manipulator could be used, which is in line with the automation, already implemented within Grundfos. However since the manipulator cannot perform all the tasks, (such as Quality tests, and starting the machines) this then needs cooperation between the operator and the manipulator. To ensure cooperation, avoiding features such as fencing and other safety measures that would prohibit this, is of the highest priority. For it to be legal to operate without fencing, the manipulator should contain certain safety features within its own software to safeguard the operator. After obtaining this knowledge, it was concluded that the operator could be replaced, and the manual labor done by the operator within the workstation could be reduced, by implementing a manipulator. This would decrease the repetitive work and the risk of getting work related health issues.

The aim of this project, as stated in the final problem statement, is to reduce the repetitive work in a specific work station within Grundfos.

There are certain aspects the manipulator must meet before implementing it in the work station. Some of these requirements are the legal and safety aspects which arise when introducing a manipulator without fencing.

The UR5, while fulfilling the payload and safety requirements, does not have the necessary reach to be able to reach all of the stations in the work station, therefore two manipulators will be used in the solving of this problem. This could also have been solved by using a UR10 instead.

Unfortunately, the motion of the two manipulators could not be tested in the laboratory, since there was only one UR5 made available in this project. Therefore two individual programs have been tested on the single manipulator. However in order to ensure that the programs work theoretically, they have been linked and test runs have been conducted in a chosen simulation program.

A kinematics analysis is made, where the forward kinematics computed the position of the end effector from specified values for the joint parameters. The purpose of the inverse kinematics is to compute the joint parameters to achieve a specified position of the end effector, this gives eight different solutions for the UR5. A trajectory generation which computes the motion of the manipulator in multidimensional space when performing movements.

Furthermore an risk assessment is conducted and from this it can be concluded that a human operator will be safe, when working inside the station. Though the gripper, the manipulators and their handling of the rotors, could possibly pose a threat to the human. This will be circumvented by redesigning the gripper as well as replacing the two UR5 with a UR10.

It was found through testing, that repetitive work was lowered which was the goal of the project. It was decreased from being high repetitive to low repetitive at an average of 77.63 seconds work cycle time. This shows that the manipulator was able to reduce physical labor within a flexible work environment.

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A Appendix

A.1 Script

```
setanaloginputrange(0, 0)
setanaloginputrange(1, 0)
setanaloginputrange(2, 0)
setanaloginputrange(3, 0)
setanalogoutputdomain(0, 0)
setanalogoutputdomain(1, 0)
settoolvoltage(24)
setrunstateoutputs([])
setpayload(0.5)
setgravity([0.0, 0.0, 9.82])
while (True):
  $ 1 ”Robot Program”
  def Prog4():
    # Program generated by RoboDK 2.0.4 for Conveyor place on
        09/05/2016 09:45:09
    # Using nominal kinematics.
    # default parameters:
    speedms = 0.3
    speedrads = 0.75
    accelmss = 3
    accelradss = 1.2
    blendradiusm = 0.001
    settcp(p[0.000000, -0.020000, 0.130000, 0.000000, 0.000000,
        0.000000])
```

```
#Conveyor move
movej([2.391101, -0.926944, 0.875283, -0.257262, -0.669508,““
3.228859],accelradss,speedrads,0,blendradiusm)““
    movel([2.4, 0.8, 1.0, -0.2, -0.6, 3.15]accelmss,speedms,0,
        blendradiusm)““
movel([2.462660, -0.647692, 1.027999, -0.323584, -0.598124,““
     3.141593],accelmss,speedms,0,blendradiusm)““
setdigitalout(8, True)““
sleep(1.0000)““
#Move to Schenk““
movej([1.441991, -1.544965, 1.235868, -1.339017, 4.738220,““
    3.038618],accelradss,speedrads,0,blendradiusm)““
movel([1.387375, -0.756426, 0.439542, -1.529626, 4.856255,““
    4.685230],accelmss,speedms,0,blendradiusm)
movel([1.381952, -0.573341, 0.651008, -1.788439, 4.798783,
    4.537856],accelmss,speedms,0,blendradiusm)
setdigitalout(8,False)
sleep(1.0000)
movel([1.387375, -0.756426, 0.439542, -1.529626, 4.856255,
    4.685230],accelmss,speedms,0,blendradiusm)
sleep(1.0000)
movel([1.381952, -0.573341, 0.651008, -1.788439, 4.798783,
    4.537856],accelmss,speedms,0,blendradiusm)
setdigitalout(8, True)
sleep(1.0000)
movel([1.387375, -0.756426, 0.439542, -1.529626, 4.856255,
    4.685230],accelmss,speedms,0,blendradiusm)
movel([-0.926770, -0.926944, 0.772483, 0.154462, 0.720996,
    0.102974],accelradss,speedrads,0,blendradiusm)
movel([-0.921339, -0.720913, 0.691204, -0.028162, 0.624006,
    0.100001],accelmss,speedms,0,blendradiusm)
movel([-0.913404, -0.698010, 0.898205, -0.257438, 0.631928,
    0.099224],accelmss,speedms,0,blendradiusm)
setdigitalout(8,False)
```

```
    # movej([2.391101, -0.926944, 0.875283, -0.257262, -0.669508,
         3.228859],accelradss,speedrads,0,blendradiusm)
    end
    Prog4()
    $ 3 "MoveL"
    $ 4 "Waypoint2"
    movel([-0.913485501419712, -0.7101648595790125,
        0.5588555081954454, 0.0940627035568233, 0.6318501555082623,
         0.09922880814265904], a=1.2, v=0.25)
  end
end
def Prog5():
  # Program generated by RoboDK 2.0.4 for UR5B serie 3 on
      18/05/2016 11:12:09
  # Using nominal kinematics.
  # default parameters:
  speedms = 0.3
  speedrads = 0.75
  accelmss = 3
  accelradss = 1.2
  blendradiusm = 0.001
  settcp(p[0.000000, -0.020000, 0.130000, 0.000000, 0.000000,
      0.000000])
  setdigitalout(8,False)
  movej([0.638257, -1.096169, 1.216606, -0.170712, 2.181817,
      -0.018959],accelradss,speedrads,0,blendradiusm)
  movel([0.575780, -0.952276, 1.065306, -0.161289, 2.119416,
      -0.015282],accelmss,speedms,0,blendradiusm)
  movel([0.520026, -0.737526, 0.955505, -0.264719, 2.063724,
      -0.012230],accelmss,speedms,0,blendradiusm)
  setdigitalout(8,True)
  sleep(1.0000)
  movel([0.521139, -0.776405, 0.839395, -0.109758, 2.064836,
      -0.012289],accelmss,speedms,0,blendradiusm)
  movej([-0.710161, -1.336649, 1.578640, -0.182640, 0.720355,
```

```
    3.130425],accelradss,speedrads,0,blendradiusm)
  movel([-0.517988, -0.855203, 0.881678, 0.023020, 0.912247,
    3.144750],accelmss,speedms,0,blendradiusm)
  movel([-0.506844, -0.832697, 1.119105, -0.237016, 0.920836,
    3.141593],accelmss,speedms,0,blendradiusm)
  setdigitalout(8,False)
  sleep(1.0000)
  movel([-0.517988, -0.855203, 0.881678, 0.023020, 0.912247,
    3.144750],accelmss,speedms,0,blendradiusm)
 sleep(10.0000)
 movel([-0.506844, -0.832697, 1.119105, -0.237016, 0.920836,
   3.141593],accelmss,speedms,0,blendradiusm)
 setdigitalout(8, True)
 sleep(1.0000)
 movel([-0.517988, -0.855203, 0.881678, 0.023020, 0.912247,
   3.144750],accelmss,speedms,0,blendradiusm)
  movej([-1.482385, -1.282961, 1.496701, -0.179401, 1.498453,
    3.100659],accelradss,speedrads,0,blendradiusm)
end
Prog5()
```