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# Automatic Sample Changer for Analysers

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<p>The objective of this Bachelor's thesis was to determine a suitable solution which is as flexible as possible to changing material samples for analysers. Requirements for the solution were that the sample changer should be able to manipulate over 500 different samples and serve at least ten analysers simultaneously. Flexibility was one of the objectives of the thesis because the client company's goal is to automate several tasks in the future and a similar system could be utilized in other tasks as well.</p> <p>Firstly, different actuator options were considered by market research to find out how the requirements of the sample changer could be met with reasonable costs. After comparing different transportation systems and robots, it was decided that the best option for this application would be a collaborative robot arm.</p> <p>To determine the most suitable solution, specifications of several collaborative robot arms from the largest manufacturers were compared. After comparing different models, Omron TM5-900 and Universal Robots UR10e collaborative robot arms were borrowed for testing from local distributors. Since the two models have similar mechanical properties the testing was mostly focused on the programming environment of the robots. Universal Robots PolyScope software proved to be the better option for the sample changer because of its more open environment and better reliability.</p> <p>SolidWorks computer aided design program was used to do two assemblies with different Universal Robots' collaborative robot models. These models were used to find out how much reach would be required from the robot to fit at least 500 material samples to its working area. According to the comparison with the CAD assemblies, a Universal Robots UR10e which is the model with most reach is the best option and should be acquired for the sample changer.</p> <p>In addition to the selection of the robot arm, some thought was given to the housing of the robot cell and gripping to the samples. The recommended gripping method for the material samples would be a vacuum gripper. The testing of the gripping will be carried out after the collaborative robot arm is acquired.</p>	
Keywords	Collaborative robot, Cobot

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## List of Abbreviations

PC	Personal Computer.
HMI	Human Machine Interface.
RS-232	Recommended Standard 232 for serial communication transmission of data.
Cobot	Collaborative Robot.
USB	Universal Serial Bus protocol for connection.
QR-code	Quick Respond code which is a matrix barcode.
SSD	Solid State Drive, which is a data storage device.
TCP	Transmission Control Protocol.

## 1 Introduction

The objective of this Bachelor's thesis is to suggest a solution for an automatic sample changer system for the calibration of analysers. The automatic sample changer will be a system that serves material samples to analysers for data collection. The customer company has several products that need to be calibrated by measuring samples in their production process. This automatic calibration system should be designed so that it can be utilized for many different products.

Currently, these analysers are calibrated by human operators and it can take one to two weeks to calibrate a unit. One analyser typically needs several different calibrations for different materials and the time needed for the calibration process depends on how many calibrations have been ordered. There is already an automated calibration cabinet that can be used for some calibrations but only for one analyser at a time. A better system that does all the calibrations that are available and for multiple analysers at once would save several working hours used for the calibration. These saved working hours could be used in other parts of the production process and increase the yield of analysers.

This thesis is mostly carried out as a market research and comparing different options to determine the most suitable system for the client company. If the proposal is feasible, two automated calibration systems will be built. One will be built in China for production and another in Finland for the use of production, and research and development.

## 2 Requirements for Automatic Calibration System

In this chapter, the requirements for the automated calibration system are covered. The production process of analysers includes the assembly, production testing and calibration. The goal of this project is to automate the calibration process which is very time consuming to a level where an operator only needs to plug an analyser into a machine and come back later to pick up the calibrated analyser.

The calibration of an analyser requires up to 200 material samples depending on the number of calibrations that a client has ordered. It has been requested to make the

automatic calibration system flexible enough to be able to do data collection with different kinds of analysers, which increases the number of different samples it needs to store.

## 2.1 Automated Calibration System workflow

Below, the workflow of the Automated Calibration System is listed from start to finish.

1. An operator places a unit into a holder.
2. The operator chooses a sample or a series of samples to be measured with given parameters from a PC.
3. The Automated Calibration System does data collection for calibrations by doing sample changing and measurements.
4. More units can be added in the middle of the process.
5. When the data collection is done, operator picks up the unit from the holder.

Calibration is done based on the results of the data collection with a calibration software. It can be done with the same PC which controls the sample changer or with any other PC with the calibration software installed.

## 2.2 Analysers

The Automated Calibration System should be able to calibrate around 10 units simultaneously and units can be removed or added to the process at any point without having to stop the process. Safety of the sample changer must be reviewed for operators to be able to retrieve calibrated analysers or bring new ones while the sample changer is moving.

## 2.3 Samples

The Automated Calibration System must support all metal and plastic samples which are currently used in calibration of the analysers. For a basic calibration, approximately 150 different samples must be measured for data collection of one unit. With additional calibrations the number of samples needed is up to 200 for one unit. Currently, approximately 500 samples are used in all the calibrations in different analyser models. For that reason, it would be ideal if the sample changer system could be able to store and use at least 500 samples. There also should be some space left or an option to expand the system in the future if more samples need to be added.

Most of these samples are cylinder shaped but their size varies. The automated sample changer must be able to reliably place all the metal and plastic samples that are in different shapes on the measuring heads of analysers. In addition to metal and plastic samples, there are coating, liquid and particulate samples. In Figure 1 some metal alloy samples are shown.



Figure 1. An example of metal alloy samples.

### 2.3.1 Metal Samples

Most of the calibration samples are metal samples. A large proportion of them are cylinder shaped cuts from a bar but their size varies. Also, some of them are cut into more pieces and because of that, they are shaped like half cylinders or cylindrical sectors. In Figure 2 some different shaped metal samples are shown. Metal samples weigh from 100g to 400g and their diameter is between 20 mm to 80 mm.



Figure 2. Different shapes of metal samples and “FLX3” plastic sample.

### 2.3.2 Coating Samples

Coating samples are used for measuring metal on metal coating thicknesses. There are 22 different samples that are currently used for calibrations. Coating thickness samples are square-shaped and flat samples as shown in Figure 3.



Figure 3. A coating sample.

### 2.3.3 Liquid Samples

There are a few liquid samples used in analyser calibrations. Liquid samples will not be implemented to Automated Calibration System for now because there are only a few of them in use and there is a risk that the liquids start leaking from the sample cups creating a mess. Liquid samples are kept in plastic cups. Choices that would prevent later implementation of liquid samples should not be made.

### 2.3.4 Particulate Samples

Particulate samples are samples in powder form, and they are kept in the same kind of cups as the liquid samples. They must be stored and measured right side up to make sure the particulates stay close to the measuring head of analyser.

## 2.4 Calibration Software

The system will be controlled by a calibration software on a PC which will handle the communication between the analysers and the sample changer. This software will be coded with National Instruments LabVIEW, which is a system engineering program. Connection options to a PC should be tested when choosing components for the sample changer to make sure it is able to communicate with the calibration software. Communication between the calibration software and sample changer must be reliable so it can be left working without supervision.

## 2.5 Mobility

The system must be constructed from parts small enough to fit through normal sized doors. When assembled the system does not need to fit through doors. There is limited amount of space in both factories in China and Finland, and therefore it would be a good solution if the sample changer is as compact as possible.

## 2.6 Cycle Time

Average measurement time for one measurement in the calibration process is approximately two minutes. Analysers should not spend more time waiting for a sample than they do measuring.

# 3 System Design

In this chapter, different parts for system solutions of the sample changer are presented and compared to find out the best solution for automated calibration. The first question to examine in the sample changer design is whether to move samples to analysers or analysers to samples. The preferred option from these two is to move samples from a storage for the analysers and back because the analysers are fragile and heavier, and therefore harder to move. The varying shapes of the samples makes them more challenging to move to the analysers for measurements.

Other important criteria to analyse when choosing the system solution are the following: how many samples it can store, how many analysers can be calibrated at the same time, and how much space it takes in the factories in Finland and China. The cost is, of course, also an important factor in the decision making. The sample changer can be assembled inside both factories and thus it does not have to fit through doors.

### 3.1 Actuators for Sample Changing

An actuator is needed to move the samples for the analysers and back. Below, different options for the actuator are considered. Some of these ideas are inspired from a visit in Teknologia 2019 fair in Helsinki.

#### 3.1.1 Cartesian Robot or Delta Robot

A cartesian robot or a delta robot would be a fast, and probably an easy and an affordable choice for the sample changer. The downside in both options is that they would take a lot of space in the factories because all the samples must be on the same plane to be reachable by these robots. Delta robots also start losing their degrees of freedom when going to extremities of their range of motion [1 p.86]. The fast movement speed these two robots have is also not very beneficial because the measurement times of the analysers are typically two minutes.

A conveyor that brings samples as trays from a storage to the reach area of the robot could be used to minimize the space needed for these robots. With this solution, all the samples would not be available for robot at once, which makes the cycle time bigger if analysers need samples from different trays. Also having more moving parts in the system adds cost because more hardware and programming is needed.

#### 3.1.2 Transport Systems

At the Teknologia 2019 fair, several transport systems were showcased and some of them could be utilized in the sample changer system.

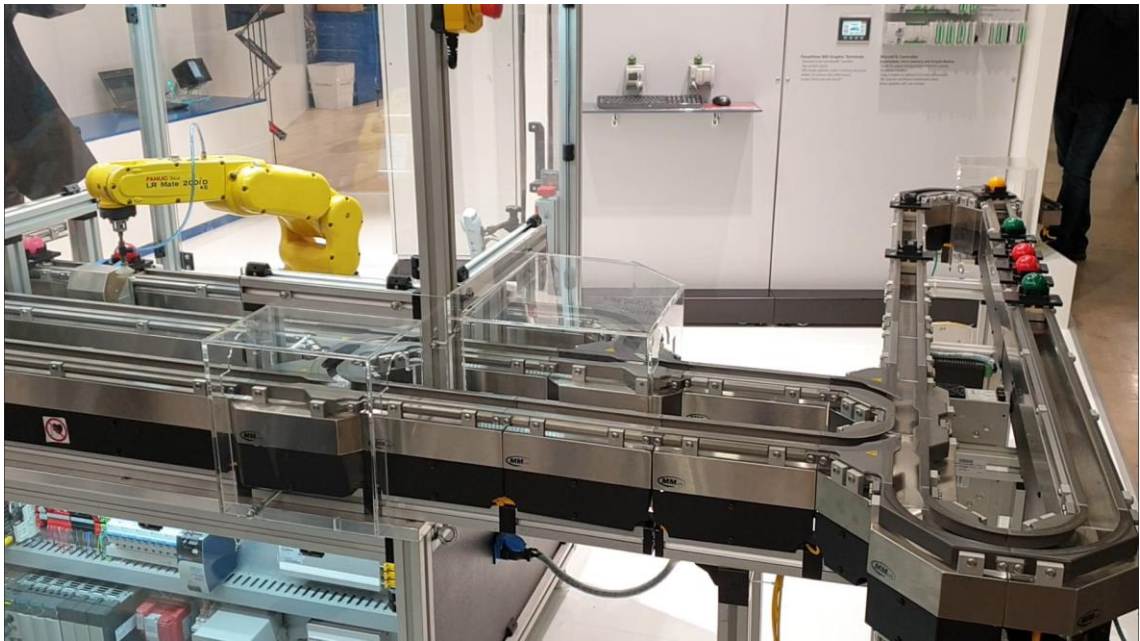


Figure 4. Linear transport system by MagneMover LITE.

In Figure 4 a linear transport system with many crossings and a Fanuc industrial robot arm are transporting and sorting plastic balls at a high speed. This kind of system would be usable as a sample changer. However, it would require many tracks and crossings to put all the samples on individual movers and be able to serve any of the samples at any time for an analyser to measure. A robot arm and a linear transport system with long tracks would make the sample changer more expensive than some of the other options shown below.

Another linear transport system that was seen at the Teknologia 2019 fair was Beckhoff XTS, which is similar to the MagneMover LITE. It has movers that move along straight or curved rails. The movers are fast and can be stopped with high precision. The downside of this system is the number of movers needed even though multiple samples could be stored on one mover. At least 50 movers would be needed for 200 samples to fit if four samples are on one mover and it would be preferable to have the option for even more samples. In Figure 5 below, is an example application of the Beckhoff's XTS system combined with machine vision and doing inspection for parts.

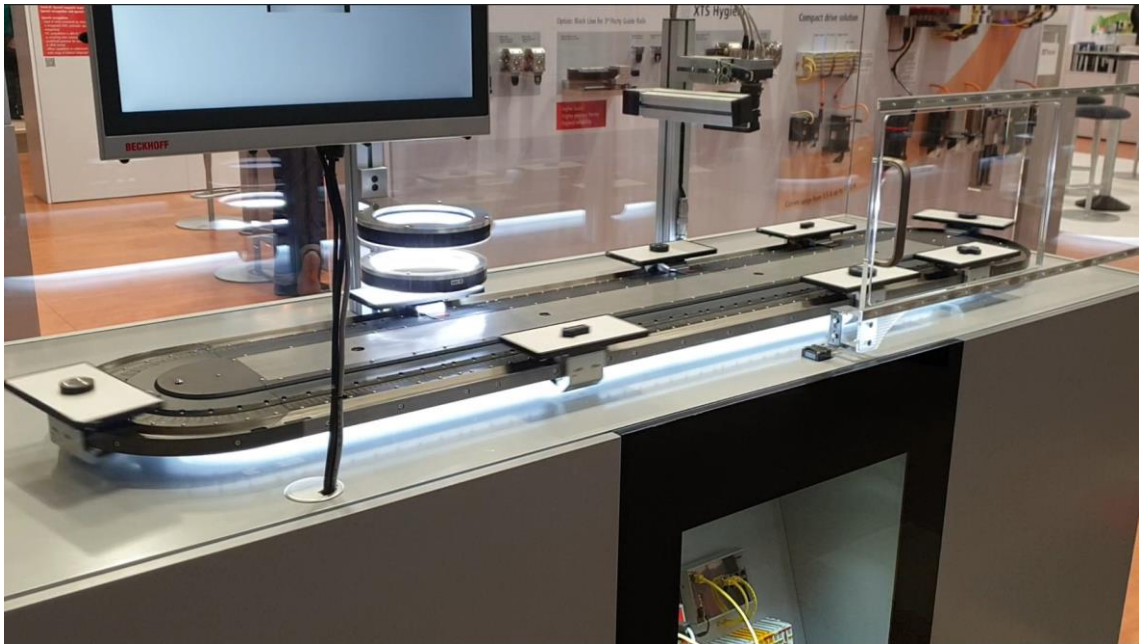


Figure 5. Beckhoff XTS moving parts for visual inspection in Teknologia 2019 Helsinki.

Beckhoff was also showcasing their new X-Planar system that can be seen in Figure 6 which uses magnetic fields to manipulate movers on a plane. The movers are floating at a height of 1 to 5 mm depending on the load and there is no physical contact between the movers and the planar tiles beneath them. The movers can reach 4 m/s speed and they have a maximum load of 6 kg for each mover. The movers can also be lifted a few millimetres or tilted 5 degrees. This system could be applicable as a sample changer. Advantages in the X-Planar system are that the movers could carry multiple samples and the analysers could be stationary and the movers could slide under the measuring heads and lift the samples for measurement. The movers can move freely on the plane and are able to pass each other which means that any sample could be delivered for an analyser at any unless it is in a mover that another analyser is measuring. Another advantage is that since there is no contact between the movers and planar tiles no metal or dust particles will form and contaminate the samples. [2]



Figure 6. Beckhoff XPlanar system showcased at Teknologia 2019 Helsinki.

### 3.1.3 Robot Arms

A robot arm would be a good solution if all the samples and analysers can be stored within its reach. This way the robot could be the only moving part of the sample changer system. This solution also allows calibrating multiple analysers at the same time because the robot could change samples for one analyser while others are measuring.

An advantage with the robot moving samples from a storage to the analysers compared to moving analysers is that the samples can be stored on the floor and walls. This way, the space needed for the sample changer is much smaller than if the samples can only be stored on one plane. An additional axis or two could be added to the robot to increase the number of samples it can reach or to decrease the size of the robot.

As mentioned in the requirements, the cycle time must be fast enough not to leave analysers waiting for a new sample for a longer time than they spend measuring a sample. The robot must be able to serve at least 10 units fast enough. The cycle time of a robot arm must be estimated to check if it can meet the requirement.

It was decided that a robot arm would be the best option for further testing of the actuator to the sample changing because of its flexibility. The client company has several other

possible applications that will be automated in the future. After buying one robot arm and learning to program it will make it easier and cheaper to automate other tasks with the same kind of robot.

### 3.2 Collaborative Robots

It was decided that a robot arm is the best option for manipulating samples because it is easy to use and should be fast enough to serve at least ten units. A robot arm is also the most flexible option. If the analysers or the samples change, the robot can still be utilized, or it can even be shifted to another job if some day it is no more needed in sample changing.

Since the automatic sample changer does not need to move objects heavier than approximately 0.5 kg and operators should be able to add or remove analysers to the automatic calibration system, it was decided that a collaborative robot or cobot should be acquired. Collaborative robots are designed to be able to work in a shared workspace with human operators.

Cobots have a lower maximum payload than some of the industrial articulated robots with the same reach but for this application it should be enough. They are also not as fast as industrial robots, but when human operators are not close, they can reach 1 m/s linear speed or more depending on the payload. When working with human operators close by, cobots are used in a collaborative mode. In collaborative mode, their tool speed is limited to 250 mm/s or less and they can detect collisions and do a protective stop before doing damage to humans or other objects in their way.

In Table 1. is a rough estimate of the cycle time for picking and placing a sample from a storage to an analyser and back with a cobot arm. With the 1 m/s maximum speed and distances given in the table a cobot should be able to serve 10 analysers in less than a 100 seconds which is fast enough given the requirement that the analysers should not spend more time waiting for a sample than measuring in the Automatic Calibration System.

Table 1. Cycle time estimation for sample changing with a cobot.

Maximum speed	1	m/s
Slow speed	0,1	m/s
Acceleration	1,5	m/s <sup>2</sup>
Dist. from home to sample	900	mm
Dist. from sample to analyser	1500	mm
Dist. from sample to home	750	mm

Movement Type	s (mm)	t (s)
Acceleration to sample	333,3	0,67
Maximum speed	233,3	0,23
Deceleration to sample	333,3	0,67
Slow approach to sample	100,0	1,00
Gripping		1,00
Acceleration to analyser	333,3	0,67
Maximum speed	833,3	0,83
Deceleration to analyser	333,3	0,67
Slow approach to analyser	100,0	1,00
Release of sample		1,00
Acceleration to home	333,3	0,67
Maximum speed	83,3	0,08
Deceleration to home	333,3	0,67
Total cycle time:		9,15

Cobots have force sensors in their joints and some of them have soft edges to make them safer to work in the same space with human operators [3]. Many cobots also have a hand-guiding function that allows easy programming [4]. Safety assessment is always required when using cobots but fencing them is usually not necessary as shown in Figure 7, where human-robot collaboration is explained with 3 levels. In level 1 workspaces are completely separated with fencing. Level 2 is the same as 1, but there is a part of the workspace shared. However, when human operator enters the works space the robot must be stopped. In level 3 with a collaborative robot the workspace is fully shared. In this case cobot must be in collaborative mode with reduced maximum speed for the safety of the human operator.

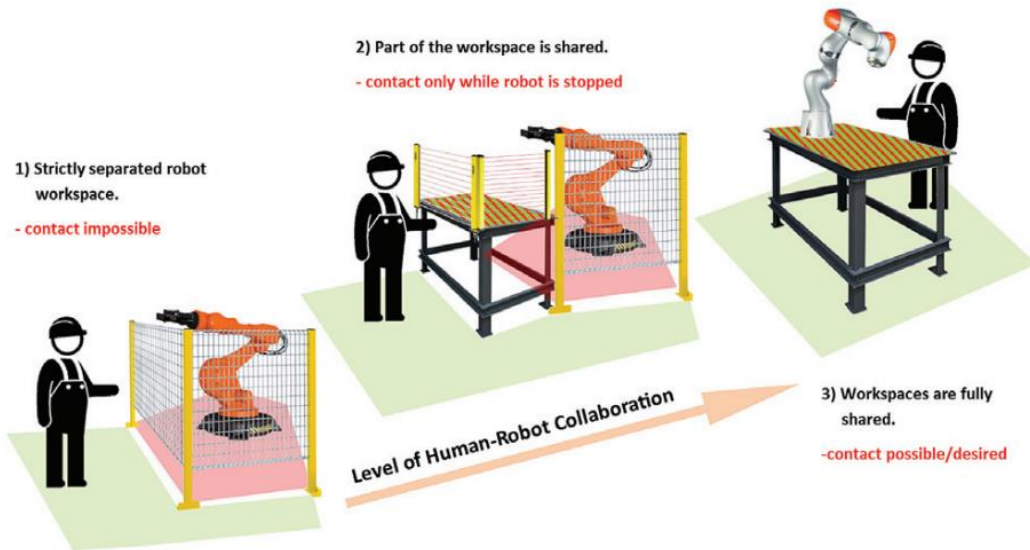


Figure 7. Different levels of human-robot collaboration [3].

One of the key factors when selecting the robot for the sample changer system is that the robot manufacturer should have customer support in China and Finland. The reason for that is that at least two robots will be ordered, one to China and the other one to Finland. Both robots should have customer support close by in case there are any issues with them for minimal downtime.

Below, some collaborative robot manufacturers and their cobot models are introduced. Omron Techman Robot and Universal Robots were picked for a closer look because they both produce models that meet the requirements for the automatic sample changer and they both have sales and customer service in China and Finland. An advantage with Omron Techman cobots compared to the other cobots mentioned above is the built-in machine vision camera that could be useful. Universal Robots, on the other hand, are market leaders in the cobot industry and their cobots have been used in many different applications. The advantage in the market leadership is that there is a large amount of third-party software and examples of different applications for their cobot models available on the internet. These can be used as instructions and can save a lot of time later in the development of the automatic sample changer.

### 3.2.1 ABB

ABB has been in the robotics business for 50 years and has installed over 400 000 robots around the world. Over the years they have produced industrial robots many different applications for example for painting, welding, automotive industries and pick and place. In 2015 they released their first collaborative robot [5].



Figure 8. ABB YuMi Collaborative Robot. [6]

ABB has two cobot models called YuMi (IRB 14000) and Single-arm YuMi (IRB 14050). YuMi is dual arm cobot that has two 7-axis robot arms and a controller for both off the arms built in one unit. Single-arm YuMi is a single 7-axis robot that has a separate controller which makes it easier to implement in tighter spaces. In Table 2. are some of the most relevant specifications of these cobots regarding their use as a sample changer. [6]

Table 2. Specifications of ABB's cobots. [6]

Product Name	IRB 14000	IRB 14050
Payload (kg)	0,5	0,5
Reach (mm)	559	559
Max TCP velocity (m/s)	1,5	1,5
Weight (kg)	38	9,5

As an actuator for sample changing in the Automated Sample Changer, the payload and TCP velocity, which means their Tool Center Point velocity are applicable. But because of their short reach, these cobot models would need for example a conveyor to bring samples within their reach. This is an issue because it would be beneficial to keep moving parts in the system minimal to make its programming as simple as possible.

### 3.2.2 KUKA

KUKA is one of the largest robotics companies in the world. The company was founded in 1898 in Augsburg and now employs over 14 000 people [7]. KUKA produces a wide range of customizable industrial robots for different applications such as welding, handling, assembly and machining. KUKA has also two collaborative robot models called LBR iiwa 7 and LBR iiwa 14, which both are 7-axis cobot arms. In Table 3. some specifications of the cobot models are shown.

Table 3. KUKA LBR iiwa 7 R800 and 14 R820 specifications. [7]

Product Name	7 R800	14 R820
Payload (kg)	7	14
Reach (mm)	800	820
Weight (kg)	23,9	29,9

There are two variants of the LBR iiwa available which differ in maximum payload and reach. The 7 R800 has a maximum payload of 7 kg that is enough for the samples used in this application and a reach of 800 mm. The 14 R820 has double maximum payload and 20 mm more reach. Both variants are also available with clean room suitable properties.



Figure 9. KUKA LBR iiwa collaborative robot.[8]

A media flange located in the wrist of the cobots for powering tools can be configured with pneumatic or electric energy supplies. As a sampler changer the 7 R800 would be the most reasonable choice because the maximum payload is enough, and the reach is almost the same as the 14 R820's. With 800 mm reach it still might be hard to reach all the samples without any other moving parts. [7]

### 3.2.3 Fanuc, Stäubli and Yaskawa cobots

In Table 4. features of 6 collaborative robots that were considered are presented. These models are all suitable options for sample changing application. Like ABB and KUKA these manufacturers are large industrial robot manufacturers that have recently come up with cobot models. Stäubli's TX2 models are both significantly heavier than all the other cobots which makes their installation and possible transportation to other applications difficult.

Table 4. Collaborative robot models that were considered. [9] [10] [11] [12]

Brand Name	Fanuc	Fanuc	Stäubli	Stäubli	Yaskawa	Yaskawa
Product Name	CRX-10iA	CR-7iA/L	TX2-90XL	TX2-90L	HC10	GP7
Payload (kg)	10	7	7	12	10	7
Reach (mm)	1240	911	1450	1200	1200	927
Degrees of freedom	6	6	6	6	6	6
Weight (kg)	39	55	119	117	47	34

In addition to the cobot arm models already introduced there are plenty of other models in the market with similar features that could be applicable for sample changing. Since they all have such similar features it was decided to test two models which are easily available and could be acquired for testing. These cobots are from Omron and Universal Robots and they will be introduced in the next two paragraphs.

### 3.3 Omron Techman Robots

In May of 2018, Omron formed a strategic alliance with Techman Robot. Omron is a large Japanese industrial automation company and Techman Robot is a Taiwanese robotics company founded in 2016 and produces collaborative robots. A special feature in their cobot line-up is that they have an integrated wrist camera for machine vision. [13]



Figure 10. Omron Techman Robots collaborative robot arm. [13]

There are four models of Techman Robots called TM5-700, TM5-900, TM12 and TM14. The biggest differences in these models are in reach and payload capacity. They are all 6-axis robot arms with safety features for collaborative applications. In Table 5., some of the features of Techman cobot models are shown.

Table 5. Payload Reach and Typical Speeds of all Techman Robots. [14]

Product Name	TM5-700	TM5-900	TM12	TM14
Payload (kg)	6	4	12	14
Reach (mm)	700	900	1300	1100
Typical Speed (m/s)	1,1	1,4	1,3	1,1

From Omron's line-up, the TM5-900 and TM12 models are the best options for this application because of their longer reach 900 mm and 1300 mm. With the longer reach they can reach to more samples. Their maximum payload capability is less than in the TM5-700 and TM14 models, but both are still enough for moving the samples that are 500 g at the heaviest.

Omron has sales and customer support in both China and Finland. An Omron Techman TM5-900 collaborative robot was borrowed from Omron Finland for tests. This cobot model has a 900 mm reach and a maximum payload of 4 kg. This cobot would be a suitable option for the sampler changer. If more samples are needed Omron's bigger cobot TM12 would be a better option because of the longer 1 300 mm reach. This cobot can, however, be used for software testing on behalf of both models because the only difference between TM's cobot models are their size. The cobot's safety circuit for its collaborative mode was always open for the safety of the tester personnel. In collaborative mode, the cobot's maximum speed is limited to 250 mm/s for making it safe to work around human operators.

The cobot was equipped with a Robotiq Hand-E gripper which is a two-finger gripper. The gripper is one of TM's Plug and Play grippers, which means that it is certified to be compatible with the cobot. A two-finger gripper is probably not the best choice for gripping flat and round samples, but its control should be similar to other grippers' that are certified for TM's cobots. [15]

### 3.3.1 TMFlow Software

Omron Techman collaborative robots are programmed with TMFlow, which is a graphical HMI made by Techman Robot. The cobot can be programmed by manual guiding or by giving orders with nodes in the graphical HMI software. The parameters of the cobot can also be adjusted with TMFlow. For example, in safety settings for a collaboration mode when working alongside humans, the possible contact points with a human operator can be set in a graphical interface. After setting the possible contact points, TMFlow calculates the maximum tool speed for the cobot to be safe to work with. When the head or neck are set as possible contact points, the cobot will not move at all. TMFlow runs on an outdated version of the Microsoft Windows operating system.

### 3.3.2 Communication

Since the cobot will be controlled with a calibration software made with LabView, the communication with a PC running a LabView program must be tested. The options for communication with the Omron Techman cobots are Ethernet (Master) or Modbus TCP/RTU. The connection with Ethernet is considered unsafe because the TMFlow software is running on an outdated Windows platform. With Modbus TCP there might also be issues caused by the security settings of the customer company's computers. Connection with Modbus is safer because the cobot should not get access to the Internet with it. Modbus RTU with an RS-232 cable from the robot controller to a PC is the best option for the communication and it will be tested.

### 3.3.3 Test Procedure

To test the connection between TM5 cobot and a PC, a Modbus test program was made with LabVIEW and a Modbus RTU connection configured with TMFlow. A robot controller was connected to a PC with an RS-232 cable. The LabVIEW program was able to send strings to the cobot and Boolean operators, for example, to command the cobot's camera light to turn on and off.

In TMFlow software, a program loop was made to test the communication and its reliability. The TMFlow program loop checked if the camera light is on and if true, the cobot moved and used the gripper. After moving, the cobot waited for a LabVIEW Modbus test programs command to turn the camera light off, and when it was turned off, the cobot

moved back to its original position and used the gripper again. The cobot also wrote a log of the movements to a USB drive connected to the controller. This loop was left running over one weekend to see how reliable the connection is.

### 3.3.4 Results

Omron Techman TM5-900 cobot met the minimum requirements for the test, which was to be able to communicate with a PC and execute commands from it. The cobot was able to read and write both string and Boolean operators in Modbus registers and coils. However, it was difficult at first and took two days and help from Omron's technical support to get a simple Modbus test program to work. When leaving the Modbus test running over a weekend there had been a connection error in the first evening and the cobot had stopped because of it. Connection errors are an issue because the sample changer should be reliable enough to be left running over night and over weekends. However, they could be dealt with better error handling that recovers the connection after an error. TMFlow software looks good and modern but when the programs get longer and more complex the nodes start to look messy and hard to perceive. The software also crashed frequently.

There was not, however, enough time to properly test the wrist camera of the cobot. It was only tested that it could read a QR-code that could be used to identify samples if they are not always in the same places. Another use of the wrist camera could be to check if a sample is placed correctly on an analyser's measuring head. A problematic issue with the wrist camera is that it can only save photos to a specific SSD that can be bought from Omron with the cobot. That makes it hard, for example, to save a service log of the cobot to a server in China and monitor it from Finland.

Omron Techman TM12 with its 1300 mm reach would be applicable for the sample changer. It is cheaper than the same-sized Universal Robots UR10 and is equipped with a built-in wrist camera. Modbus RTU communication with a PC is possible but its reliability was not convincing in the test because of the connection error and TMFlow software crashes.

### 3.4 Universal Robots

Universal Robots is a robotics manufacturer that was founded in 2005 and sold their first robot and the first collaborative robot called UR5 in 2008. UR is only focused on developing and manufacturing collaborative robots. [16]

The newest cobots introduced in 2018 from Universal Robots are called e-Series. There are four different sized models, UR3e UR5e UR10e and UR16e. The biggest difference between e-Series and older UR models is that the e-Series cobots have a force/torque sensor built in their wrist. In addition to the force/torque sensor, there are also smaller improvements made to the e-Series compared to the older CB-Series UR cobots. These smaller improvements are for example, better repeatability and lower power consumption and noise level. A force/torque sensor can however be installed also to the older CB-series cobots. [17]

Table 6. Universal Robots e-series cobot models. [18]

Product Name	UR3e	UR5e	UR10e	UR13e
Payload (kg)	3	5	10	13
Reach (mm)	500	850	1300	1100
Typical Speed (m/s)	1	1	1	1

As shown in Table 6., the UR3, UR5 and UR10 models grow in payload and reach but UR13 has a heavier payload capability and a shorter reach than UR10. The CB-series line-up cobots have the same specifications as the e-series cobots shown in Table 6.

#### 3.4.1 Universal Robots testing

An UR10e cobot was borrowed from Oy Machine Tool Co, which is a Finnish distributor of Universal Robots. It was used to test how the connectivity to a PC and the PolyScope software which is used to program the robot compares to Omron's products. This cobot was equipped with the same Robotiq Hand-E gripper as the Omron TM5-900 that was tested earlier. Safety during the testing was managed by using safety zones which limit the area where the cobot can operate. If the cobot attempts to enter the safety zone it will cause a protective stop. This way it was possible to test the cobots movement with high accelerations and speeds safely when all personnel were outside of the safety zone limits that had been set. The cobot that was tested is shown in Figure 11.

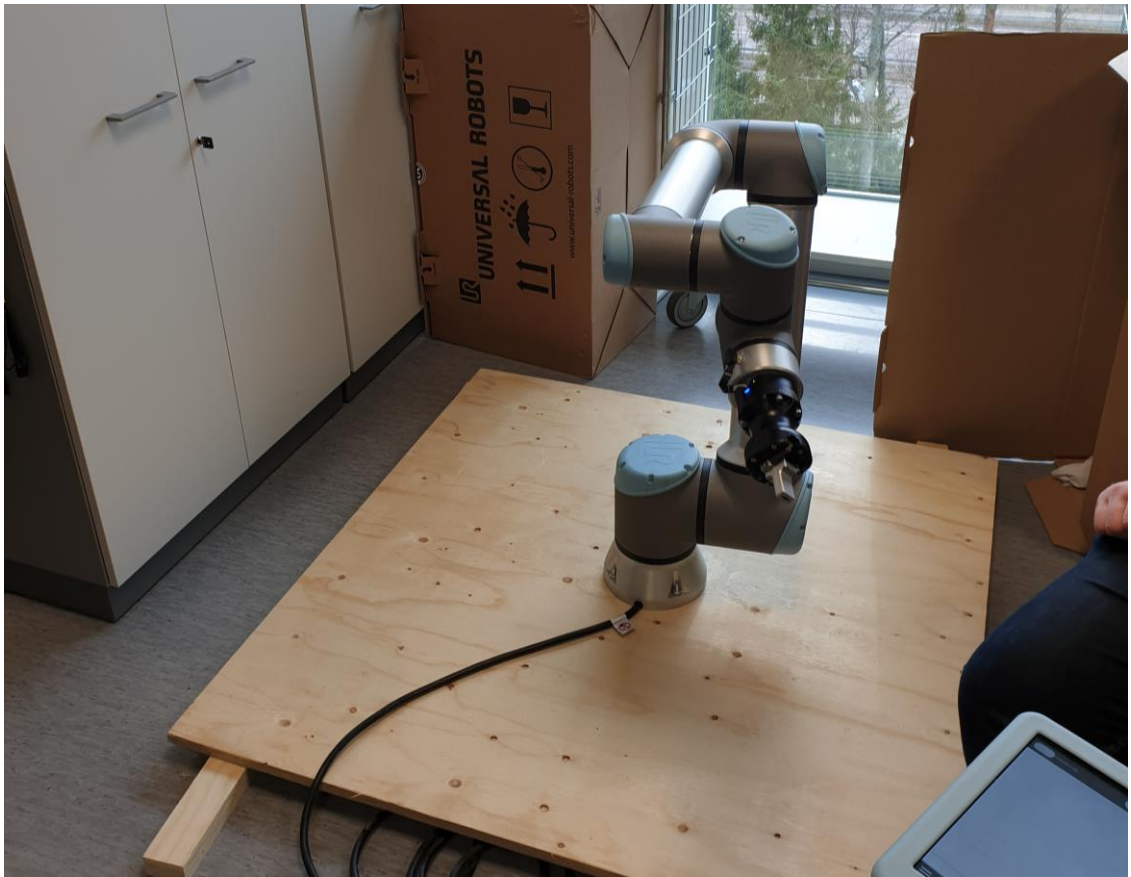


Figure 11. UR10e cobot being tested in the customer company's facilities.

Universal Robot cobots are programmed with a touch screen teach pendant panel which is connected to the cobot's controller box. PolyScope is a graphical user interface running in a Linux based operating system that is used with the teach pendant to program the cobot [19]. In Figure 9. is an overview of the PolyScope software in the teach pendant. There is also third-party software available for offline programming and simulation for Universal Robots cobots. Offline programming could be beneficial when making changes to the robot program in Finland and putting them to service in the factory in China.

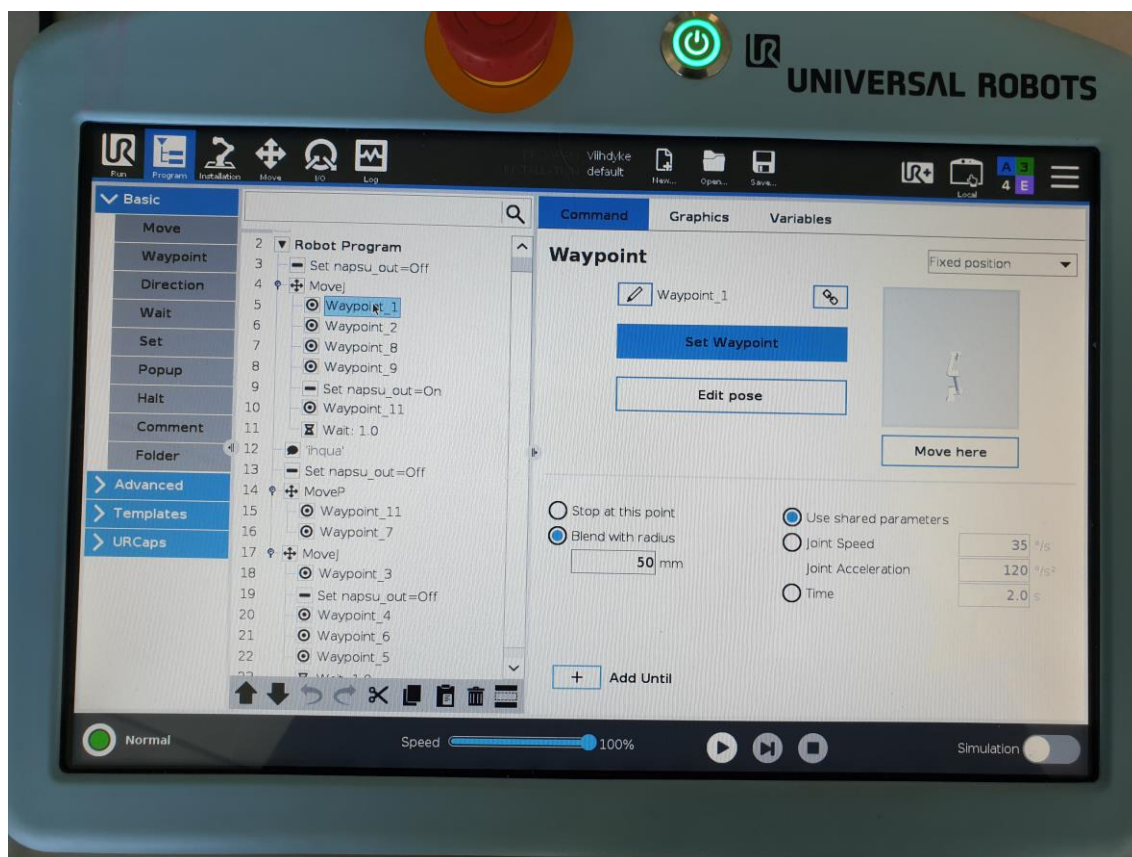


Figure 12. Overview of the programming environment in PolyScope using the teach pendant.

To test the cobot, a couple of programs were made with different movements to see how the PolyScope software and different commands work. In Figure 12 an overview of the PolyScope software can be seen. The software was easy to use, and it did not crash during the two days of testing with the cobot. Connectivity to a PC, which will be used to control the cobot was tested using Modbus TCP. The Universal Robots control box does not have an RS232 connector, so an Ethernet port had to be used to connect the robot to the PC. A LabVIEW program was used on the PC to send commands to the cobot that can be for instance play, pause or shutdown and read the status of the cobot. The LabVIEW program was also able to send URscript commands, which can be used to set coordinates, joint angles and speed and acceleration for the cobot. The Modbus connection was easier to configure with Universal Robots than with Omron's cobot because numerous instructions for the Universal Robots can be found from the Internet. Another way of communicating between a PC and the Universal Robot is TCP socket communication, which was not tested because of lack of time, but it should be also tested if a Universal Robots cobot is acquired.

The only benefit in an Omron's compared to a Universal Robots cobot is the included wrist camera, which can however be bought separately to the Universal Robots cobot. Otherwise the Universal Robots cobot seemed easier to use regarding its programming and configuring the connections between a PC which will be controlling the cobot with the calibration software in the automatic calibration system. This is mostly because of Universal Robots being the market leader in the cobots market and widely used in different applications. This was seen when visiting the Teknologia 2019 fair where the generality of cobot applications were showcased by using Universal Robots cobots. Based on these tests a Universal Robots cobot is the best option from these two for this sample changing application.

### 3.5 Sample Storage

Sample storage will be the system where the material samples are stored and in the reach of the actuator moving them to the analysers. Each one of the samples should be reachable at any time to enable the calibration of multiple analysers at the same time without having to wait too long for samples. Sample storing must be considered to find out how much reach is needed from the cobot that will be acquired for the sample changer. A few options for the cobots housing were considered to find out the most efficient way to fit as many samples as possible to the reach of the cobot.

To optimize the size of the cobot cell to hold as many samples within the cobot arms reach as possible, the cell should be round shaped. This is because the cobot arms workspace is round shaped as of its rotating joints. Rooms or other spaces in the factories though are usually not round shaped so the amount of floor space saved would not be significant and a round shapes are more challenging design and build than a square shaped box. For that reason, it was decided that a cubic-shaped design should be used in the cobot cell.

Two simple assemblies of a cubic-shaped cobot cell were made using Dassault Systemes Solidworks, which is a computer-aided design program. A smaller assembly was made with a UR5 cobot and bigger one with a UR10 cobot. The models of the cobots were downloaded from Universal Robots website. These models were created to determine how many samples could be fitted to a cubic-shaped cobot cell and how beneficial would a cobot with a longer reach be regarding the number of samples that can be fitted.

As mentioned in the requirements 500 or more samples would be preferred to fit to the Automated Calibration System. A Robotiq E-Pick vacuum gripper was used as an example gripper in both assemblies to help determine how the cobot arms can reach the samples.

In Figure 13 is a screen capture of the assembly with a UR5 cobot assembled into a cubic-shaped cell with a 1500 x 1500 mm floor and 1300 mm height. The cobot is lifted 500 mm from the floor level to make it able to reach below and above for as many samples around it as possible. The 10 holes in the cross bar in front of the cell are for the measuring heads of the analysers that will be calibrated. Ten analysers could be fitted in a row and more could be fitted underneath or above if needed, which meets the requirements. On the three walls of the cell the samples can be fitted on shelves as seen in the screen capture. These shelves are placed by an estimation on how much space would be needed for one sample and in the UR5 assembly 96 samples could be placed in each wall. The total number of samples that could be placed is 288 on the walls and some samples could also be placed on the floor of the cell, which is approximately 350 samples in total.

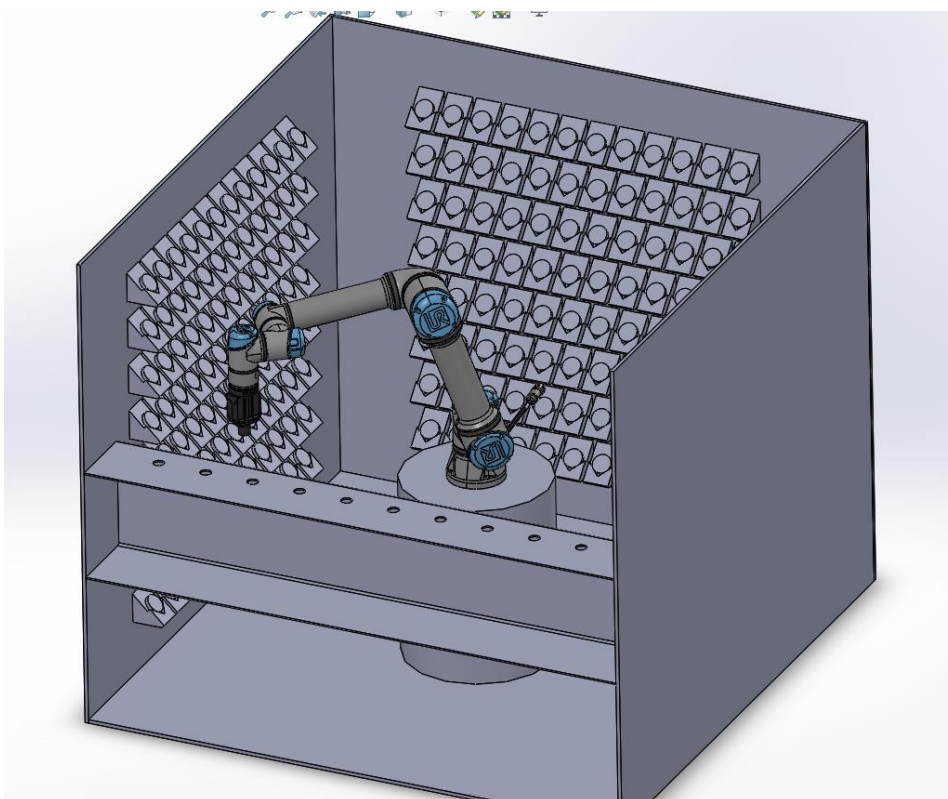


Figure 13. Screen capture of a UR5 cobot cell in SolidWorks.

To test if the cobot can reach all the samples, its joints were mated together, and their degrees of freedom were limited. This way the cobot model was able to be manipulated in the program similarly as a real one would move.

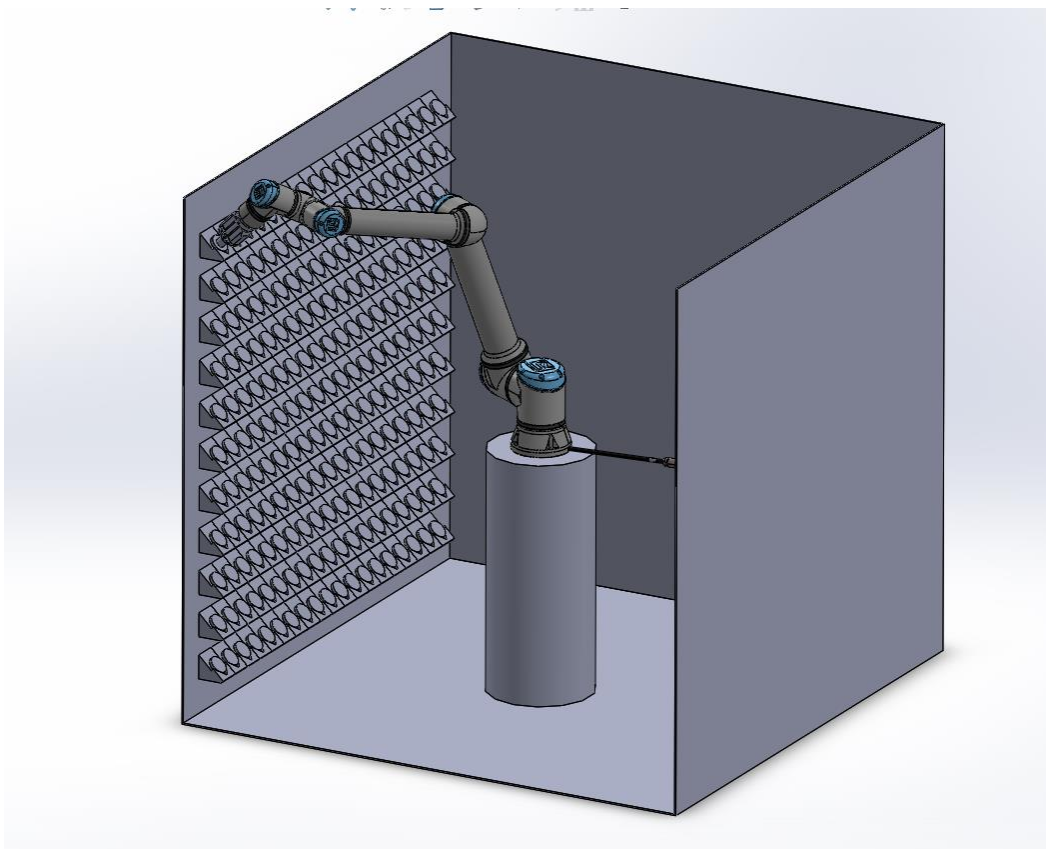


Figure 14. Screen capture of a UR10 cobot cell in SolidWorks CAD program.

The CAD assembly with a UR10 cobot in Figure 14 is in a considerably larger cell with 1750 x 1750 x 1750 mm dimensions. This model is even more simplified than the one with a UR5 cobot because it was only made for checking how many more samples could be fitted if a cobot with more reach is used. With a UR10 cobot in a larger cell 209 samples can be fitted on each wall and there is also more floor space, which makes a total of approximately 700 samples. This is considerably more than can be fitted with UR5 cobot and more than the required amount.

The shelves used in the SolidWorks models are not an efficient way of using space. The reach of a UR5 cobot would be enough if the space is used more efficiently. This can be done with several commercially available solutions. One example is using drawers, which can be opened and closed by the cobot or automatically. Another option would be a paternoster storage machine, which is a vertical carousel with shelves. Using the cobot

to open drawers or to manipulate any kind of sample storage would slow down the rate of samples being served for analysers, which could make it impossible to meet the cycle time requirement were units should not spend more time waiting for a sample than measuring. Automated storages would not slow down the cycle time, but they are expensive and require more programming work because there would be more moving parts in the system. A cobot can also be placed upside down to the roof of the system, which would free up more space for samples on the floor. A rigid chassis would be needed for the system if the cobot attached to the roof to hold the forces that are generated when the cobot is accelerating. The final placement of the cobot can be decided in the detailed design of the Automated Calibration System. In conclusion shelves around the cobot cell and on the floor is the best option for sample changing.

### 3.6 Grippers

When borrowing the two cobots from Omron Finland and Machine Tools it was decided to use the time in testing to determine which cobot has better connectivity and software for the robot programming, because that is the biggest difference between the two cobot models. For that reason, there was not enough time to test the gripping to the samples. Gripping to the samples should not be very difficult because while the samples are in different shape, they have some similar features for instance they all have a flat top surface and they weigh less than 0,5 kg. A couple of gripping methods were considered for the sample changer and they should be tested later once a cobot is acquired to find out which is most suitable.

#### 3.6.1 Parallel grippers

Parallel grippers or two-finger grippers have two jaws or fingers that can grasp to an object to move it. There are several options of these kinds of grippers commercially available and many of them are compatible with the UR10 cobot [15]. Parallel grippers are the simplest kind of grippers. A difficulty with them in this application is that their lack of flexibility [14 p.94-96]. Because of the different shaped samples, it is difficult to grasp them all with the same parallel gripper. Another difficulty is with flat samples. Gripping them would require high precision from the cobot to be able to grasp the thin edges. In Figure 15 is the Robotiq Hand-E parallel gripper which was borrowed for testing with the UR10e cobot arm.



Figure 15. Robotiq Hand-e parallel gripper attached to the UR10 cobot.

The gripping of different shaped samples could be handled by implementing an identical shaped block to all samples. This could be done by gluing or with double-sided tape, but it would require specific materials to make sure the blocks do not cause interference to the measurements the analysers make. With a square-shaped block, rotation of the samples could be eliminated when gripping which is an advantage because some of the samples must be oriented correctly to cover the whole measurement head of the analysers because of their small size.

### 3.6.2 Vacuum grippers

Vacuum grippers use suction for gripping to surfaces. They can be powered with an external air supply or an internal electric motor to provide suction [18]. There are several vacuum grippers available that are compatible with Universal Robots cobots [15]. In Figure 16 is a Universal Robots cobot equipped with a Robotic E-pick vacuum gripper which has an internal power supply for suction.



Figure 16. Universal Robots cobot equipped with a Robotiq E-Pick vacuum gripper.

Vacuum grippers are the most promising option for the sample changer because they should be able to grip almost all samples without any modification to the samples form. This is because all the samples have a flat top surface which is a good contact surface for the vacuum grippers. Exceptions are liquid and particulate samples, which might need a flat attachment on top of them to make them easier to grip with a vacuum gripper.

A challenge with using a vacuum gripper is releasing the samples in the correct orientation every time. If the samples are picked and placed several times their position after releasing might start to travel or they might start to rotate.

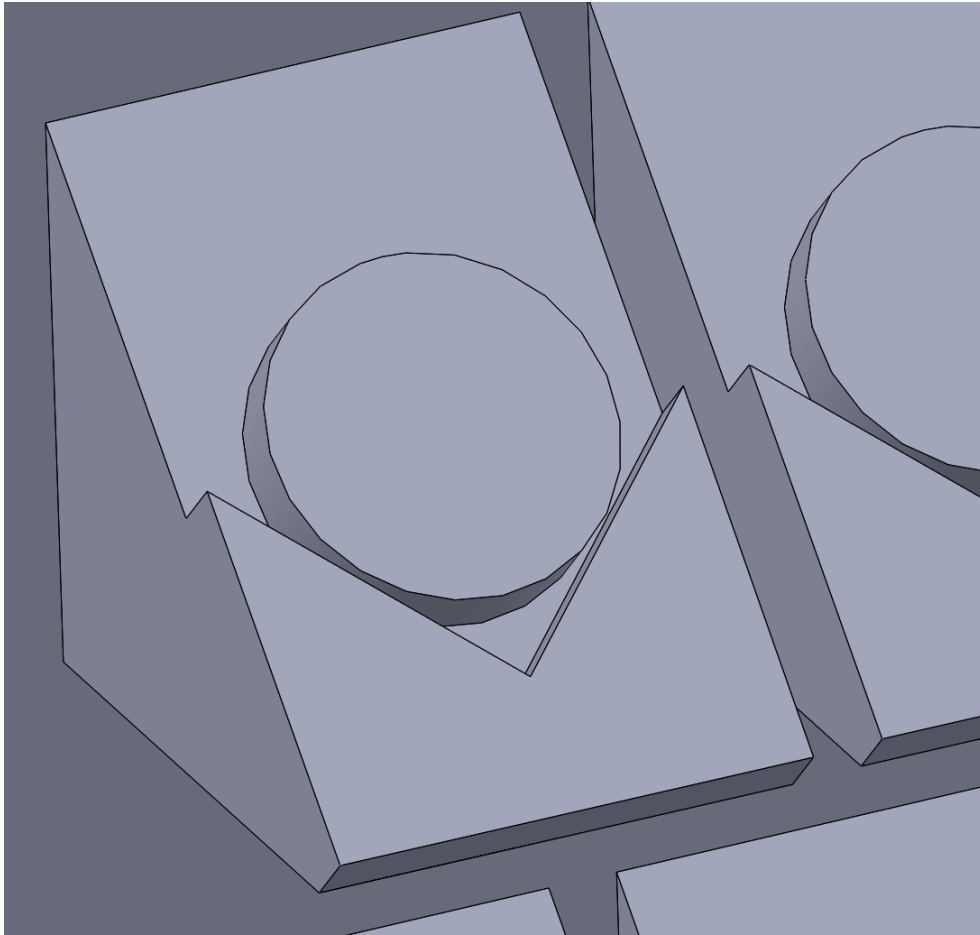


Figure 17. Sample shelf from the simplified CAD model of the sample changer.

Travel and orientation change of the samples after picking and placing them can be eliminated by storing them in oblique shelves as shown in Figure 16. The V-shaped bottom of the shelf will return the samples position and orientation as it was before gripping it. The shelves must be made of a material with low friction to enable the samples to slide to correct position. They should not be made from metal to avoid contamination of the metal samples.

## 4 Summary

This Bachelor's thesis was mainly focused on finding out the best manipulator for sample changing from the current market. Some thought was also given to gripping of the material samples and the housing of the cobot cell. Two collaborative robot models were tested to find out which one is the best option to acquire for the sample changing application. Universal Robots UR10e was better than the Omron's TM5-700 mainly because its programming environment was more open, and therefore easier to control externally with a calibration software from a PC.

The UR10e meets all the requirements mentioned in chapter two and it is cheaper than the transportation systems that were considered. Universal Robots cobots can also be used in other automation projects and the knowledge gained in this project can be utilized when programming these robots.

The next step in the project is starting to do detailed design of the cobot cell and acquiring the UR10 cobot for more testing and design of the calibration software can be started. Gripping to the samples should also be tested and it should be started with a vacuum gripper as suggested in the thesis.

Since all the Automated Calibration Systems requirements had to be considered when choosing the manipulator, the thesis will also give a good overall picture of the whole calibration automation project. This will be helpful when going into more detailed design of the system since there are several designers working with different tasks in this project. Based on this thesis, estimation of the savings and the cost of this automation project can also be made.

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