DESIGN OF A WALL PAINTING ROBOTIC SOLUTION

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Mechanical Engineering and Production Technology — Abstract

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The aim of this thesis project was to design and test a wall painting robotic solution. The thesis topic was commissioned by HAMK Tech Research Group.

Modern cities come with high apartment buildings, and the structures of their rooms are almost similar. Traditionally, human workers have been working on painting those walls. As the work is repetitive and labour intensive, there is a possibility for automation. Therefore, HAMK Tech wanted to employ a collaborative robot for the wall painting operation and to analyze the test results.

A cost-effective wall painting system was designed using airless paint technology available in the market. In the end, a painting test was performed inside the Robotics lab of HAMK using a Universal Robot. The programming required for the test was done offline using URSim. After the test, a new end effector was designed, which used an electrical actuator instead of a pneumatic actuator, making the system more compact.

The result of the test was a smooth and consistent painting operation. This report presents documentation of the design features, calculations, test setup, and Cad models.

Keywords: airless Painting, collaborative robots, universal robot, wall painting Robot
Pages: 37 pages and appendices 8 pages

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List of Abbreviations

ATOS = 3D Scanning Software

CAD = Computer-Aided Design

DOF = Degree Of Freedom

3D = Three Dimensional

HAMK = Hämeen Ammattikorkeakoulu

Kg = Kilogram

mm = Millimetres

STL = Stereolithography

UAS = University of Applied Sciences

1 INTRODUCTION

Technology is evolving faster than anytime before, and so is automation. One of the sole purposes of automation is to exclude humans from the dangerous, repetitive and less value-adding task. We have been using automation to save time, effort, and energy, and we will continue searching for various areas where automation could be applicable.

Wall Painting is considered as a labour intensive and constant attention-demanding task. The repetitive nature of the painting process makes it a very boring job for the human worker. Moreover, the harmful chemicals contained in the paint could cause respiratory problems in humans. Automating the process will have several benefits such as quality control, repeatability, waste reduction and faster cycle times. Additionally, automation could also reduce labour costs and decrease the possibility of blunders. (Megalingam et al., 2020, p. 1). These factors were the motivation behind the development of an automated robotic solution in the project.

1.1 Commissioning Party

The Commissioning party for the project was HAMK Tech Robotics Research Group. HAMK Tech is a research unit within Häme University of Applied Sciences which is specialized in sustainable technology solutions. Their main areas of research are the metal and building industry, combining expertise in chemistry, mechanical engineering, construction engineering, electrical engineering, automation engineering and energy technology. Figure 1 shows the different areas and branches of HAMK Tech. The aim of the unit is to promote efficiency and sustainability in the use of natural resources and also to help people in using ecological technological solutions. (Hämeen ammattikorkeakoulu, 2021)

Figure 1. HAMK TECH (Hämeen ammattikorkeakoulu, 2021)

1.2 Objective

The commissioning party wanted to examine the possibility of automation in the wall painting operation. Thus, the main objective of the project was to design a spray-painting system for UR5e and to perform the painting test. The report describes the technical background, the design process and the results achieved.

HAMK Tech owns different collaborative robots, which include MR200 and UR5e. Hence, the wall painting solution was planned for those two robots. The design of the painting system included UR5e, which was mounted on MiR200.

2 COLLABORATIVE ROBOTS (COBOTS)

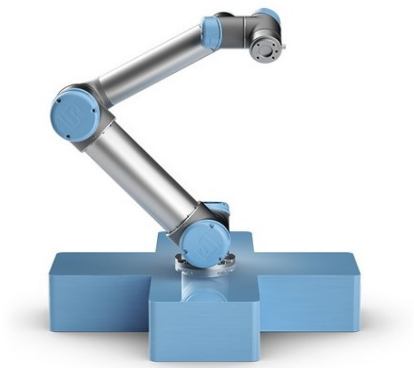
Collaborative robots are built to work safely along with human workers in the shared workspace. They are used to perform repetitive and labour-intensive tasks while a human worker works on complex and thought – intensive tasks. They are integrated with sensors to avoid collisions and emergency stops to shut down the system in an emergency. Their capacity to work with humans increases the possible application of robotic automation in various areas. The demand for collaborative robots is expected to grow exponentially because various industries realize the potential profits from this technology. It is predicted that the market will reach 7.5 billion USD in value by 2027. (*What Are Collaborative Robots, Cobots | RIA Collaborative Robots*, n.d.)

Figure 2. Human-Robot Collaboration (Robotics Online Marketing Team, 2019)

2.1 UR5e

UR5e, illustrated in Figure 3, is a mid-range collaborative robot arm manufactured by Universal Robots. It is a lightweight, highly flexible industrial robot with a payload of 5 kg. The robot arm can easily be optimized in collaborative operations like picking, placing and testing. The working radius of the robot is up to 850mm. Easy programming, fast setup, high degree of safety and fast payback times are the attractive features of this robot. (Universal Robots, n.d.)

Figure 3. UR5e (Universal Robots, n.d.)



2.2 MiR200

MiR200 is an autonomous mobile industrial robot that is safe and cost-effective. It is a collaborative robot with a payload of up to 200 kg and a run time of 10 hours with a fully charged battery. It is generally used in internal transportation and logistics. The robot can move independently and perform tasks automatically. MiR200 is shown in Figure 4.

Figure 4. Mir200 (MiR200, n.d.)

3 ROBOT'S PROGRAMMING

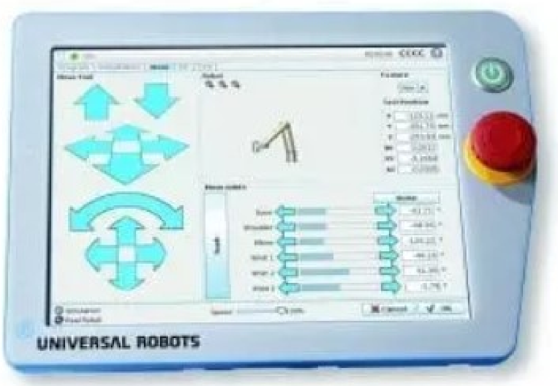
In the early days, programs were written by punching a load of holes into paper stripes and by feeding these to the computers. Similarly, the strips needed to be rewound into a spool to reload the program. Figure 5 shows a programmed paper strip. Although modern robotics has developed drastically since then, it uses the same basic concept of 1s and 0s. There are many ways to program a robot today. However, popular three programming methods are discussed in the following. (Owen-Hill, 2016)

Figure 5 Programmed paper strips (Owen-Hill, 2016)

3.1 Teaching Pendant

Teach Pendant programming is the most used robot programming method today. ‘‘According to the British Automation and Robot Association, over 90% of robots are programmed using this method’’(Owen-Hill, 2016). The modern-day teach pendants looks like a touchscreen tablet connected to the robot. Figure 6 represents a modern day teach pendant. The programming can be done by pressing the button on the teach pendant and by manually moving the robot from point to point. After saving the entire programme, the robot can playback the points at full speed. (Owen-Hill, 2016).

Figure 6. Teach Pendant (Universal Robots - Olympus Technologies Robot Integrator and Supplier, n.d.)



Advantages

- Teach pendant programming is already familiar to many technicians
- Precise positioning can be achieved
- Simple movements like straight line motion can be programmed quickly and easily

Disadvantages

- The entire system gets disrupted because of the Robot downtime
- There is a training requirement to learn to program

3.2 Lead through

The force sensor or a joystick placed right above the wrist moves the robot, and the positions are stored inside the robot computer by the operator. Various collaborative robots have integrated this programming method into their system. (Owen-Hill, 2016)

Advantages

- Faster than teach pendant programming method
- Does not require prior knowledge of 3D CAD or programming
- Detailed tasks can be done easily which may require many lines of codes in offline programming

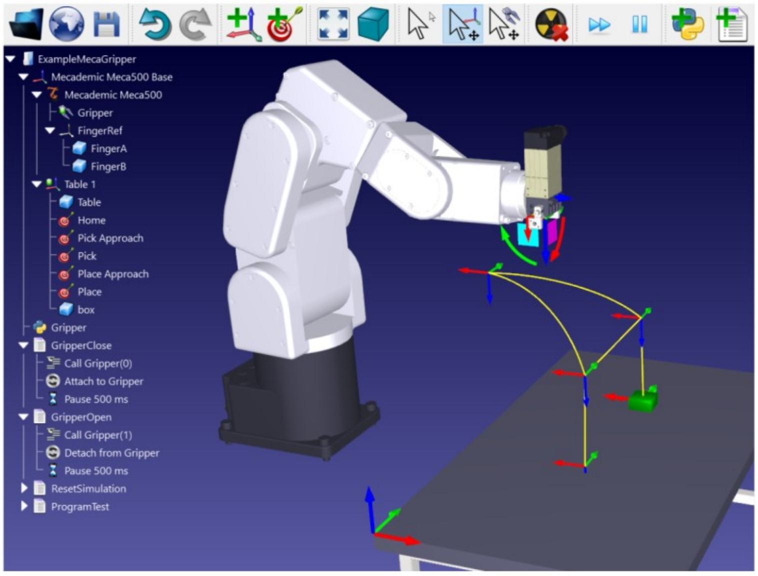
Disadvantages

- Long downtime
- Precise coordinates movement is difficult
- Not suitable for tasks that involve algorithm

3.3 Offline programming

Usually, researchers use offline programming to ensure the functionality of advanced control algorithms before using them on the real robot. At the same time, industries are also using office programming for better efficiency. Offline programming involves writing programs and virtually simulating the task. The advantages and disadvantages of this method are discussed below. (Owen-Hill, 2016). Offline programming interface can be seen in Figure 7.

Figure 7. Offline Programming inside RoboDK (Owen-Hill, 2016)



Advantages

- Short robot downtime as the programming is done offline.
- Various approaches can be tested at the same time.

Disadvantages

- Change in the programme may be required as the virtual world does not completely represent the real world.
- More time required overall.

4 Existing automatic painting solutions

Although various research has been done on wall painting robots, there are no working solutions in the industry at the moment. However, there are solutions which have shown phenomenal results. Two of the most advance solutions are mentioned in the following.

4.1 PictoBot

PictoBot is a collaborative robot that can work alongside human workers in a repetitive interior wall painting process. It is designed to operate in high elevations freeing humans from tiresome work like climbing, bending, kneeling and reaching. The robot constitutes a 3-DOF mobile robot, 1- DOF long – reach jack-up mechanism, a 6-DOF industrial arm, an airless paint pump, a painting head system and a computer-controlled system. A Mobile robot on which all the subsystems are mounted is free to move around the construction site, which is sufficient to paint corners and surfaces. A working PictoBot is shown in Figure 8. PictoBot is equipped with a sensor-driven painting system, which helps it to adapt to various environmental changes at the construction site. (Asadi et al., 2018, p. 91)

Figure 8. Wall Painting Robot (Nanyang Technological University, 2016)

4.2 Okibo

Okibo is an autonomous robot, which can operate alongside human workers on a construction site. The robot arm is equipped with a 3D scanner that can 3D scan indoor structures and act accordingly. It can also perform automatic path planning. It operates using batteries for indoor operations. A fully functional Okibo robot can be seen in Figure 9.

Figure 9. Okibo Robot

5 ELECTRONIC COMPONENTS

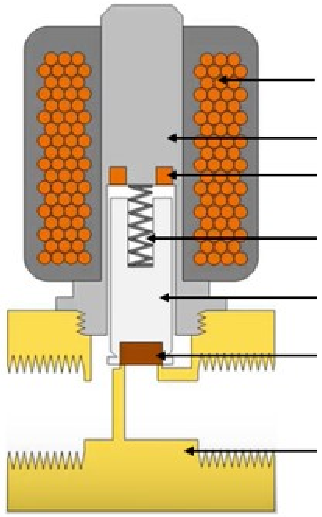
5.1 Servo Motors

A servo motor is a rotatory actuator or a motor that allows for precise control in terms of the angular position, acceleration, and velocity. It combines a standard motor with a sensor to get the position feedback making it superior to regular motors. The most important types of servo motors are Ac servo motor, Dc servo motor, brushless DC servo motor, positional rotation servo motor, continuous rotation servo motor, and linear servo motor. A regular servo motor contains three wires power, control and ground. Servo motor functions on the PWM (Pulse Width Modulation) principle, which means the duration of a pulse applied to the control pin, controls its angle of rotation. Robotics, Conveyor belt, camera autofocus are some of the applications of servo motors. (Goel, 2018)

5.2 Solenoid Valves

Solenoid valves are electromechanical valves that are used to control the flow of fluids. The centre of a solenoid valve consists of an electric coil called solenoid and a movable ferromagnetic core known as a plunger. Figure 10 shows the interior of solenoid valve. When an electric current passes through the coil, a magnetic field is created. The magnetic field generates an upward force on the plunger, resulting in an open orifice. (tameson, n.d.)

Figure 10. Solenoid valve (tameson, n.d.)



5.3 End Effectors

The device that is attached to the robot’s wrist and allows the robot to interreact with its task and environment is knows as end effector. There can be various types of end effectors such as grippers, Force – torque sensors, material removal tools, welding torches, collision sensors, Tool changers etc. A few of them can be seen in Figure 11. (What Is an End Effector and How Do You Use One?, 2020)

Figure 11. End Effectors (Bélanger-Barrette, 2016)

6 MECHANICAL COMPONENTS

6.1 Linear Guides

A linear guide consists of two parts: a block and rail. The block moves linearly along the plane on which the rail is placed. There are recirculating bearings inside the block which create the motion along the rail. Linear guides are used in various machines. For instance, the 3D movements of a machine table are created using linear guides. (Gonzalez, 2015)

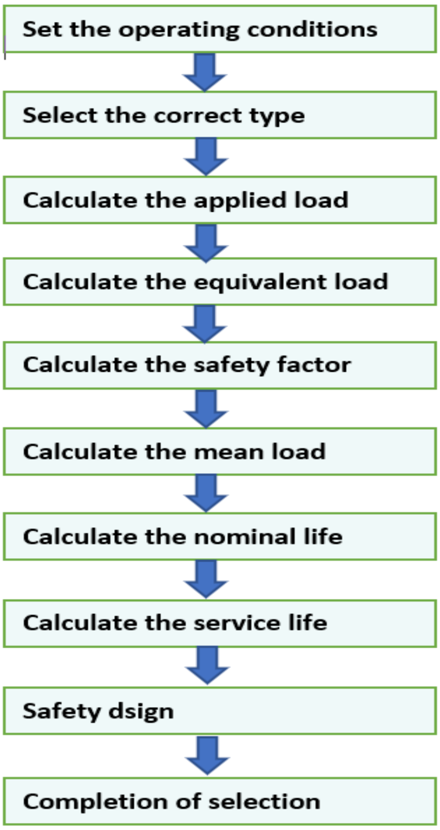
Features of Linear Motion are described below:

- Due to the very little friction during the movement of a linear guide, they are highly accurate in the long run.
- They have high rigidity as there is an equal load rating in all directions and a self – aligning capacity to correct installation errors.
- Compared to traditional sliding systems, linear guides provide high precision even with milled or ground mounting surfaces which makes them very easy for maintenance.
- The power required to move the system is low due to the low friction providing very high speed.

6.2 Selection Procedure of Linear Guide

The required linear guide can be selected based on the procedure in Figure 12.

Figure 12. Selection procedure of linear guides



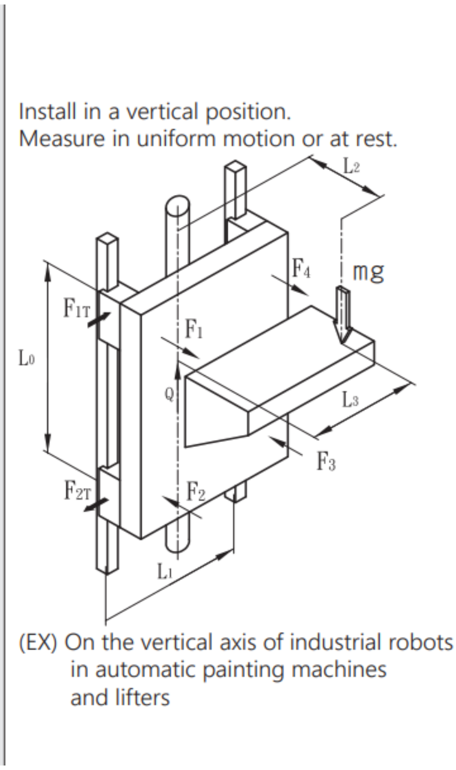
6.2.1 Working load

Different factors such as the location of the centre of gravity of an object being moved, the location of the trust produced, inertia due to acceleration and deceleration during starting and stopping, and the machining resistance determine the required load and these conditions must be considered to calculate the accurate applied load (E-Catalog, n.d.)

6.2.2 Calculation of Working Load

The magnitude of an applied load can be calculated based on the operating conditions. Figure 13 shows the operating condition of an industrial robot in lifters and its working load can be calculated based on formula below. (E-Catalog, n.d.)

Figure 13. Uniform motion (E-Catalog, n.d.)



For the calculation of the working load the following parameters must be known:

1. Mass: m (kg)
2. Direction of the action load
3. Location of the action point (e.g. center of gravity) : L_2, L_3, h_1 (mm)
4. Location of the thrust developed : L_4, h_2 (mm)
5. Linear Guide system arrangement: L_0, L_1 (mm)
6. Velocity diagram

   Velocity: V (mm/s)

   Time constant: t_n (s)

   Acceleration : a_n (mm/s)

   $a = (V/t_n)$

   Gravitational acceleration g = 9.8 m/s
7. Duty cycle (No : of reciprocating cycles per min) : N_1 (min^{-1})
8. Stroke lemgth: L (mm)
9. Mean velocity : V_m (mm/s)
10. Required service life in hours : L_h (h)

The following equation can be used to calculate the applied load when linear guides are installed in a vertical position, moving in uniform motion or at rest.

$$F_1 = F_2 = F_3 = F_4 = (mg*L_2)/2*L_0 \quad (1)$$

$$F_{1T} = F_{2T} = F_{3T} = F_{4T} = (mg*L_3)/2*L_0 \quad (2)$$

Where,

F_1,F_2,F_3,F_4 and F_{1T},F_{2T},F_{3T},F_{4T} are the Radial and Lateral loads.

6.2.3 Static Safety Factor (f_s)

''The static safety factor (f_s) indicates the ratio of a linear motion system load carrying capacity to the load exerted there on'' (E-Catalog, n.d., p. 07). It can be calculated with the formula (3). Static safety factor limits can be in from Table 1.

$$f_s = C_0 / P \quad (3)$$

C_o = basic static load rating (N)

P = Calculated load (N)

Table 1. Static Safety Factor Limits (E-Catalog, n.d.)

Machine Used	Loading Conditions	f_s lower limit
Ordinary Industrial Machine	Receives no vibration or impact	1.0-1.3
	Receives vibration and impact	2.0-3.0
Machine Tool	Receives no vibration or impact	1.0-1.5
	Receives vibration and impact	2.5-7.0

6.2.4 Calculation of Nominal Life

The total distance which a linear motion system cover before developing flaking is known as nominal life. Nominal life of a linear motion system with balls can be calculated using the following equation.

$$L = \left(\frac{f_h \cdot f_t \cdot f_c}{f_W} \cdot \frac{C}{P_C} \right)^3 \cdot 50 \quad (4)$$

C : basic dynamic - load rating (N)
P_c : calculated load (N)
f_h : hardness factor (Appendix 2)
f_t : temperature factor (Appendix 2)
f_c : contact factor
f_w : load factor (N)

6.2.5 Calculation of Equivalent Load

There are loads and moments from all direction acting against the linear guide, which includes radial load (P_R), reverse–radial load (P_L), and lateral load (P_T), simultaneously.

M_A : Moment in the pitching direction
M_B : Moment in the yawing direction
M_{AC}: Moment in the rolling direction

Figure 14. Directions of Load Exerted on Linear guide (E-Catalog, n.d.)

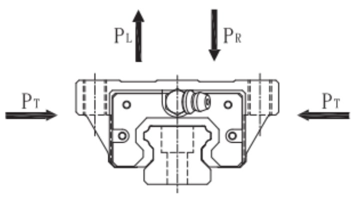
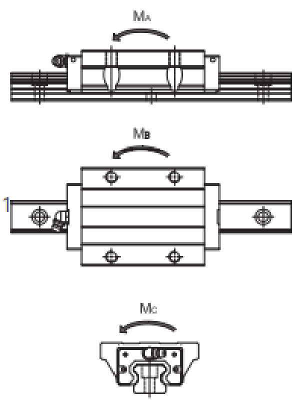


Figure 15. Direction of Moment Exerted on Linear Guide (E-Catalog, n.d.)



Equivalent Load (P_E) can be obtained by using Equation 5.

$$P_E = X*P_{R(L)} + Y * P_T \quad (5)$$

$P_{R (L)}$: Radial load
X,Y =1

6.3 Actuators

These are mechanical or electromechanical devices that provide controlled motions or positions. They use electricity, fluids such as air, hydraulics etc to operate. Linear and rotary are the two basic movements of actuators. Sometimes actuators are even operated manually. Linear actuators are normally used in pushing and pulling operations and they operate by converting energy into straight-line motions. Whereas, an operation requiring rotatory motion uses rotatory actuators. (Complete Guide to Actuators (Types, Attributes, Applications and Suppliers*)*, n.d.)

6.3.1 Pneumatic Linear Actuators

The devices that converts energy of compressed air into mechanical linear mechanical motion are known as pneumatic linear (What Is a Pneumatic Actuator and How Does It Work*?*, n.d.). They operate by repeated opening and closing of valves and used in operations where the use of electricity might be hazardous. (What Is a Pneumatic Actuator and How Does It Work*?*, n.d.)

6.3.2 Electric Linear Actuators

The device that converts the rotational motion from an electric motor to a linear motion is known as an electric linear actuator. The screw of the actuator is rotated by a motor to get the linear motion. They are used in operations like pushing, pulling, raising and lowering a load or rotating a load. They are well known for providing clean and safe motions. While using electric linear actuators, the operator has full control over the motion. Moreover, they possess a long lifespan with very little maintenance. A typical linear actuator can be seen in Figure 17. (*Part 1: What Is an Electric Linear Actuator and How to Choose It?*, 2017)

Figure 16. Electric linear actuators (Part 1: What Is an Electric Linear Actuator and How to Choose It?, 2017)

7 3D PRINTING

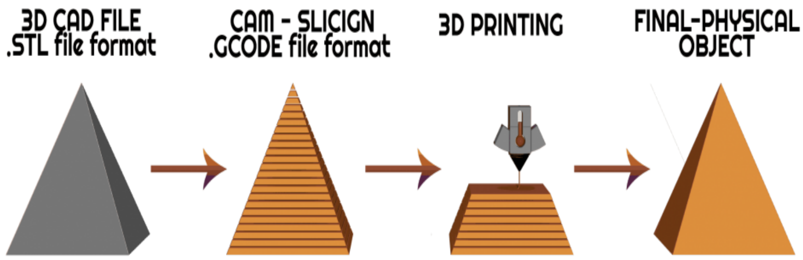
The process of 3D printing involves producing a physical 3D object by adding materials layer by layer until the desired form is obtained. Variety of materials can be used to 3D print an item, from plastics like ABS, PLA, PETG and Nylon to metals like Aluminium, Steel and Gold. First, a model is designed inside 3D modelling software. Also, a 3D scanned model can be used and saved in an .STL file format. Those .STL files are sliced using Slicer software to get the G codes. Finally, the printer uses those G- codes to print the object. Figure 18 shows the process involved in printing. (Kollataj, 2016, p. 17)

Different types of 3D printing techniques are listed below:

- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Fused Deposition Modelling (FDM)
- Digital light Process (DLP)
- Multi Jet Fusion (MJF)
- Polyjet
- Direct Metal Laser Sintering (DMLS)

- Electron beam melting (EBM)

Figure 17. Steps of 3D printing (My 3D Concepts LLC, 2017)



3D printing has already impacted various industries in different sectors. They are getting consistently more efficient, available and affordable every day. Although they had many limitations initially, the technology evolved over time and is used in different industries like manufacturing, medical, aerospace, automotive, entertainment, and military. 3D printing technology is developing and growing at a very high pace. It is also being used in simple prototyping due to its simplicity and affordability. (Adeleke, 2018, p. 1)

8 AIRLESS PAINTING

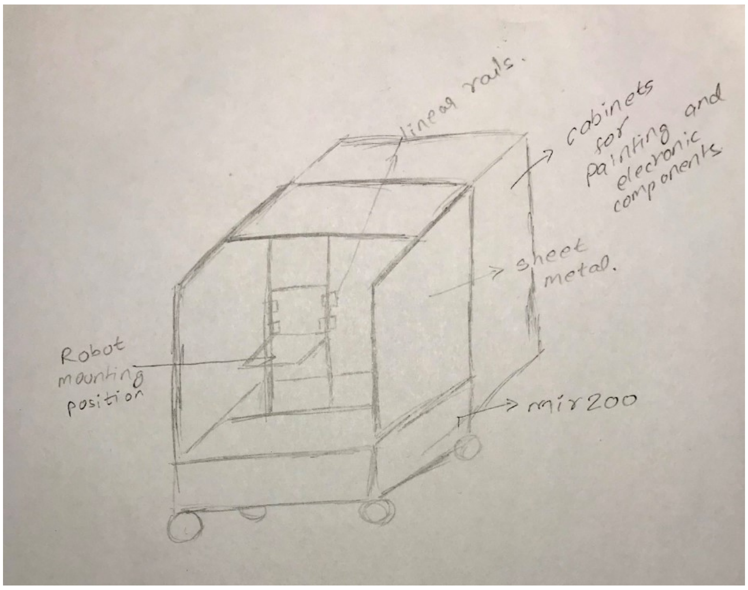
Airless spraying is considered as the fastest and most versatile method to get professional painting results. They can be used with a variety of materials. Also, airless paints are up to ten times quicker than brush painting and at least four times faster than rollers. (Intro to Airless Paint Spraying, n.d.)

The airless system uses high pressure to pump the fluid through a spray gun where size and pressure determine the flow rate. The fluid leaves the tip of the spray gun with high speed, and when it hits the air, the fluid separates into tiny droplets that make the spray pattern.

9 Concept Design

The main idea at the initial phase in this project was to provide a robot with an extended motion to increase the reach while painting. The system was planned to be mounted on a mobile robot platform, where the mobile robot could move freely in any desired direction. A rough sketch of the initial concept is shown in Figure 19. Linear guides were considered for the movements and 2mm sheet metal for the body design. Similarly, the concept of using separate cabinets for the electronic and painting system was also considered.

Figure 18. A rough sketch of the initial concept



10 SELECTED PARTS

10.1 Wagner Airless Control 150M

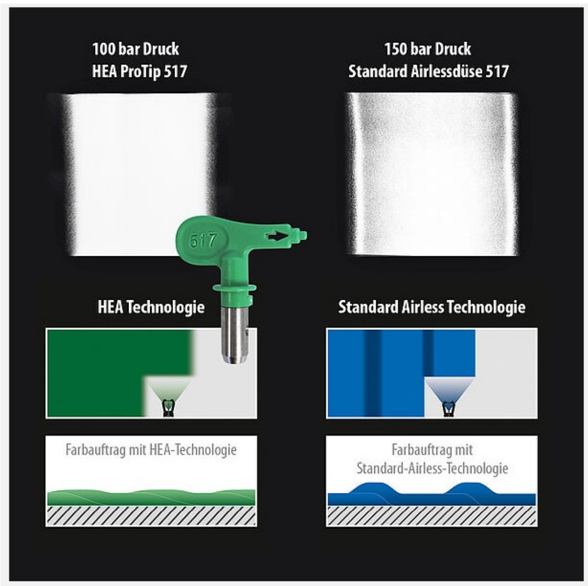
The best method to paint the wall using a robot arm is to spray paint. Spray paint requires uniform motion throughout the painting process. The robot arm can move consistently for an extended period of time. Thus, combining spray paint with a robot arm can yield the best painting result.

High-Efficiency Airless Technology (HEA) from Wagner was selected because it was ideal for the operation in the building sites. Moreover, it has the following advantages over standard airless technology. Figure 20 shows the painting system whereas figure 21 describes the difference between airless and HEA spray. (Wagner Group, 2019)

- HEA spray devices needs 55% less overspray than conventional airless technology.
- The spray patterns are improved and lines are less visible.
- The devices of HEA technology has long service life.
- It can also be used with varieties of materials.

Figure 19. Airless Sprayer Control 150M (Airless Sprayer Control 150 M, n.d.)

Figure 20. Differences between standard airless spray and HEA airless technology (Wagner Group, 2019)



10.2 T-Slot Aluminium Extrusions 45x45

T – Slot 45x45 aluminium extrusion was selected to build the frame of the painting system. Aluminium is lightweight and rigid, which made it a suitable material choice for the design. Moreover, aluminium can also be easily cut, assembled and connected.

10.3 Selected Pneumatic Components

A pneumatic cylinder from SMC with the stroke length of 20mm was selected for the design. The maximum allowable pressure of the cylinder was 0.7MPa. Similarly, solenoid valve from Festo was selected to control the motion of pneumatic cylinder. The model chosen was MSZE-3-24 DC. It uses 1.28 Watt power and 24 Volt DC. Figure 22 shows a pneumatic cylinder whereas figure 23 shows a solenoid valve.

Figure 21. Pneumatic cylinder from SMC

Figure 22. Solenoid Valve from FESTO

10.4 Linear Guide

Based on the selection procedure mentioned with Figure 12, calculations were made. Based on the calculations (Appendix 1), the best option for the design was chosen. TRH20VN model was selected with its load rating of 3696kgf. The technical data of the model can be seen in Appendix 2.

11 DESIGN OF END EFFECTOR

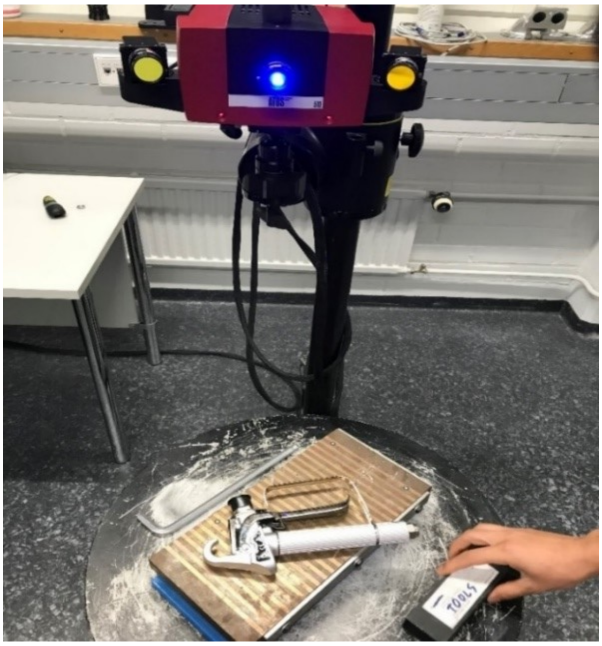
The main functions of the end effector were to hold the spray gun and the pneumatic cylinder rigid. The design was done based on the functionality requirement. A functional and rigid end effector was designed and the stages involved in the design are discussed below.

11.1 3D scanning and Reverse Engineering

Reverse engineering is a very effective method to obtain the accurate shape and dimensions of an object. Usually, the scanned data from the scanner is transferred to CAD software in order to perform reverse engineering.

The spray gun was 3D scanned at the laboratory of HAMK. Figure 24 displays the 3D scanning process. ATOS was used to record data from the scanner. Mesh obtained from the scanner was converted into .STL file. The exported .STL file was reversed engineered inside Creo Parametric 4.0 to get the exact shape of the gun.

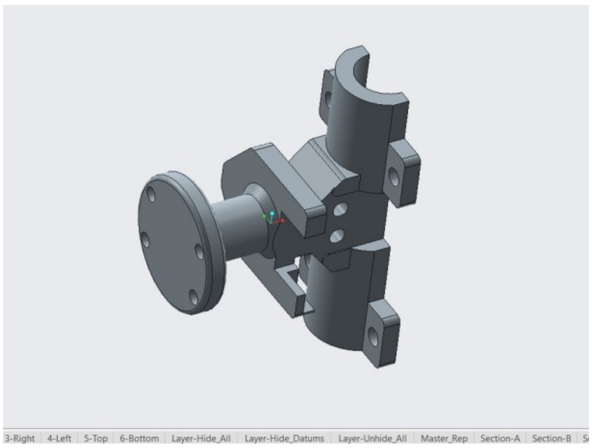
Figure 23. 3D Scanning Process



11.2 3D Modelling

The end effector was 3D modelled based on the dimensions obtained from reverse engineering. The design involved a housing for the paint gun and the pneumatic cylinder. The part was designed in Creo Parametric 4.0 . Figure 25 shows the CAD model of the design.

Figure 24. 3D model of the End Effector

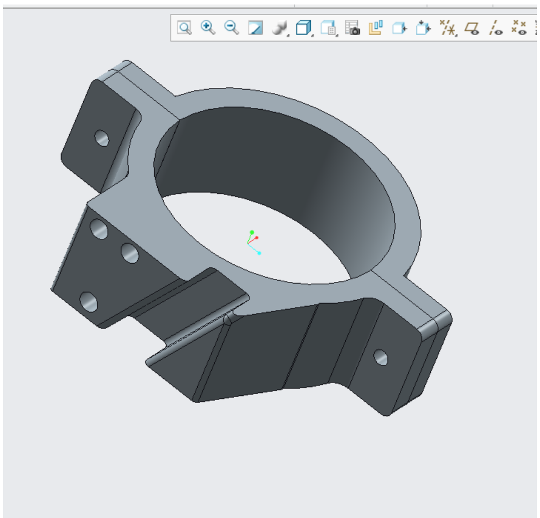


12 WIRE MANAGEMENT

Wire Management could be a major problem when working with an airless sprayer, solenoid valves and pneumatic cylinders because there could be many wires and hoses. These might disturb the operation of painting. Therefore, a proper planning of wire management is required.

A holder was designed for the arm of UR5e which could guide wires as well as hold the solenoid valve in place. A 3D model of the holder is shown in Figure 26.

Figure 25. Holder for the solenoid valve and guide for the wires



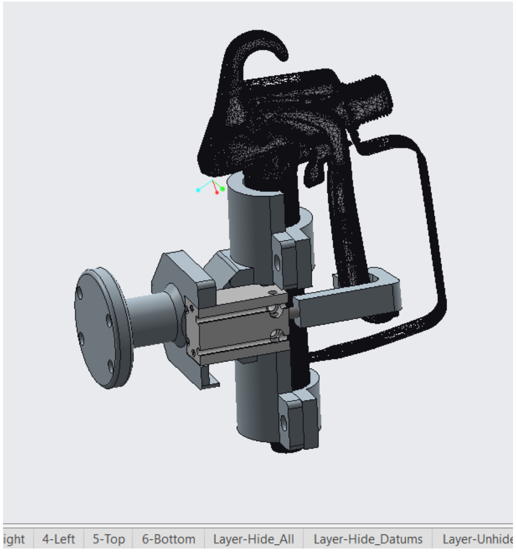
13 DESIGN OF A PAINTING SYSTEM

A complete painting system was designed based on the initial concept. The features of the design are described in the following.

13.1 Pneumatic Switch

The trigger of the paint gun was controlled through the output signal of robot controller. The output 24V from the controller send to the solenoid valve. Solenoid valve was connected to the pneumatic actuator, which controlled the trigger motion. The CAD model of the design is shown in Figure 26.

Figure 26. End Effector with Pneumatic Switch



13.2 Frame Design

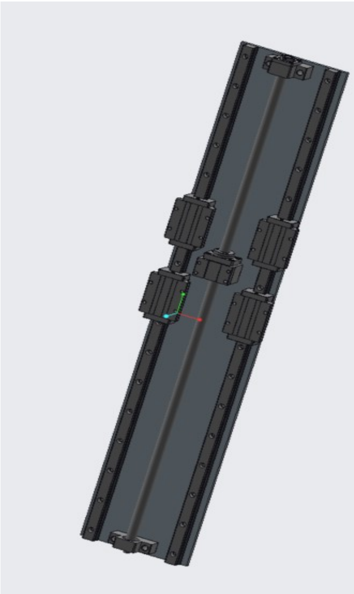
The frame of the system was composed of aluminium extrusions. Various lengths of extrusions were connected together using corner brackets to achieve a stable skeleton. The overall frame of the design can be seen in Figure 28.

Figure 27. Frame of Painting System

13.3 Linear guides and lead screw

A combination of linear rails and the lead screw was chosen to achieve the consistent uniform vertical motion. The combination allowed the robot to move vertically 1000mm, resulting in smooth painting operation. Figure 29 presents the complete setup of linear guides and lead screw

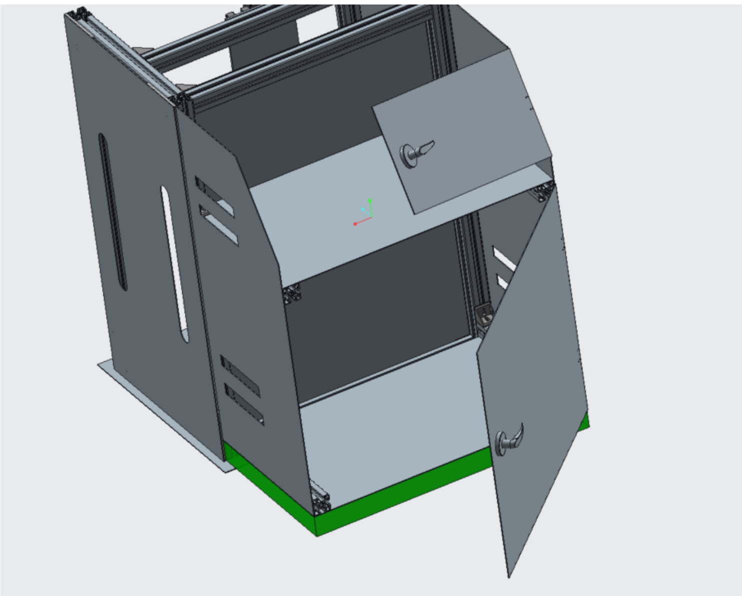
Figure 28. Combination of Lead Screw and linear guide



13.4 Compartments

Two separate compartments were designed in the system. The upper compartment was for the painting equipment where as lower compartment was for electronic components. The two compartments can be seen in figure below. The main purpose for the separation was to avoid splattering of paint into electronic components which could cause damage to the electronics.

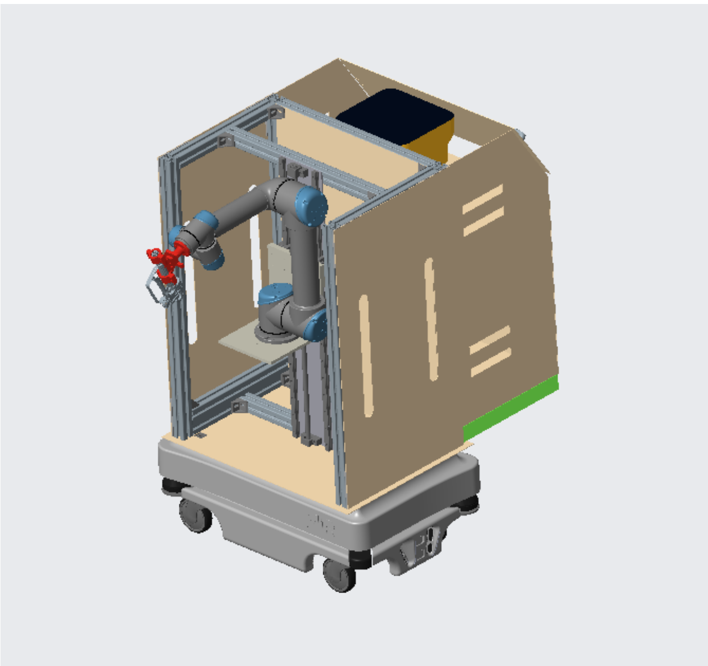
Figure 29. Compartments



13.5 Complete System

Figure 31 shows the complete design of the system. The painting system contains UR5e and the entire robotic system is mounted on MiR200. The Wagner painting system was placed into the top compartment so that the painting hoses could easily be connected to the end effector.

Figure 30. Rendered Picture of the Overall Design



14 TEST AND PREPARATION

14.1 3D Printing

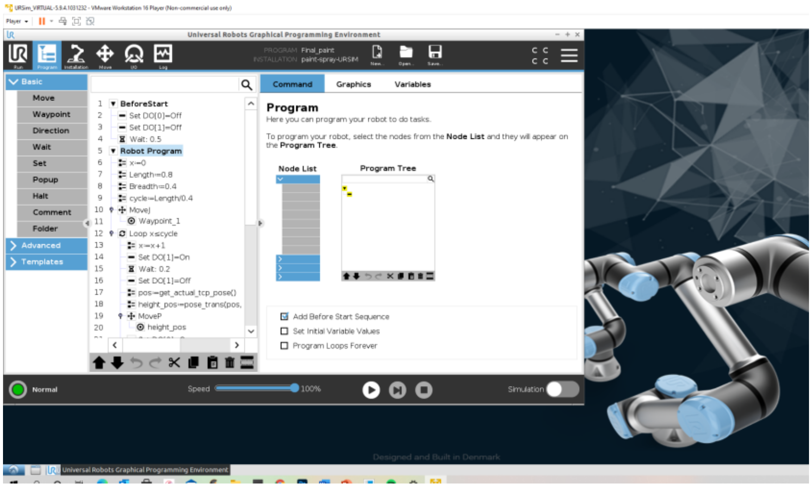
The CAD file of end effector and the holder were converted into the . STL format. Those files were imported to Slicer 3r to get the g codes . The final print was done in Prusa i3 in the Robotics Lab using the obtained g codes. PETG was used as a filament. Figure 32 shows the print results.

Figure 31. 3D Printed Parts

14.2 Offline Programming and Simulation

Programming is crucial part in automation .The programming required for the test was done offline inside virtual environment of the universal robot called URSim. URSim required Linux operating system therefore, VMware Workstation player was used to simulate Linux environment. Figure 33 shows the user interface of Polyscope simulated inside VMware.

Figure 32. Offline programming



14.2.1 Program

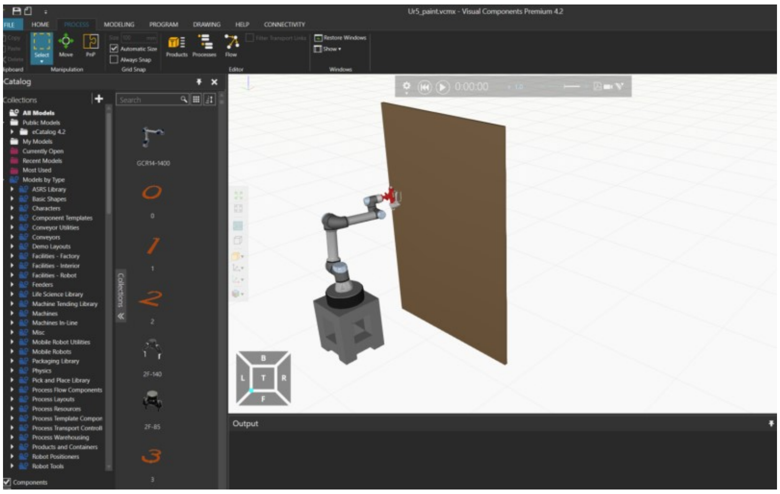
The program was written using variables. The length of the wall and the breadth of the wall must be entered at the beginning as per the need. Then, the program calculates the cycles required to paint the area automatically. Since sensors are not involved in the test, the initial position of the robot also needed to be set manually.

The program controls the solenoid valve, which is connected to the output of the robot controller. When the robot reaches the initial position, a 24V output signal is sent to the solenoid valve. The solenoid valve then triggers the paint gun and, the painting process starts. Similarly, when the robot reaches the top position, a 24V DC from the robot controller turns off the paint. Refer to the Appendix 3 for the complete program.

14.2.2 Simulation

The written program was first tested inside virtual environment of visual components. The user interface of Visual Components can be seen in Figure 34. The UR5e was imported the 3D world and the controller of URSim was connected virtually to the robot inside visual components. Then, the robot inside visual component could be controlled from URSim. Finally, the test was done and minor adjustment were made after.

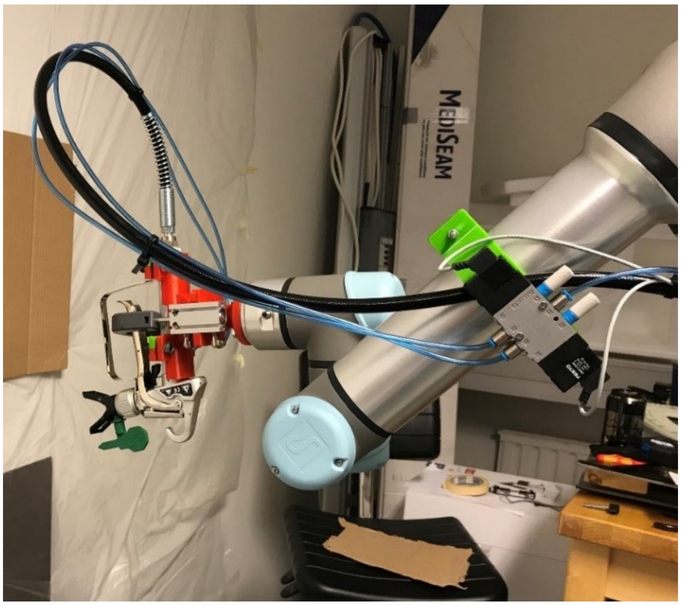
Figure 33. Simulation inside Visual components



14.3 Setup and the test

The offline program was installed inside the controller of UR5e. The weight and the Centre of Gravity of the end effector was calculated using the software of UR5e. The test was performed inside the Robotics lab of HAMK. A white water soluble paint was used for the test. Figure 35 shows the set up for the test.

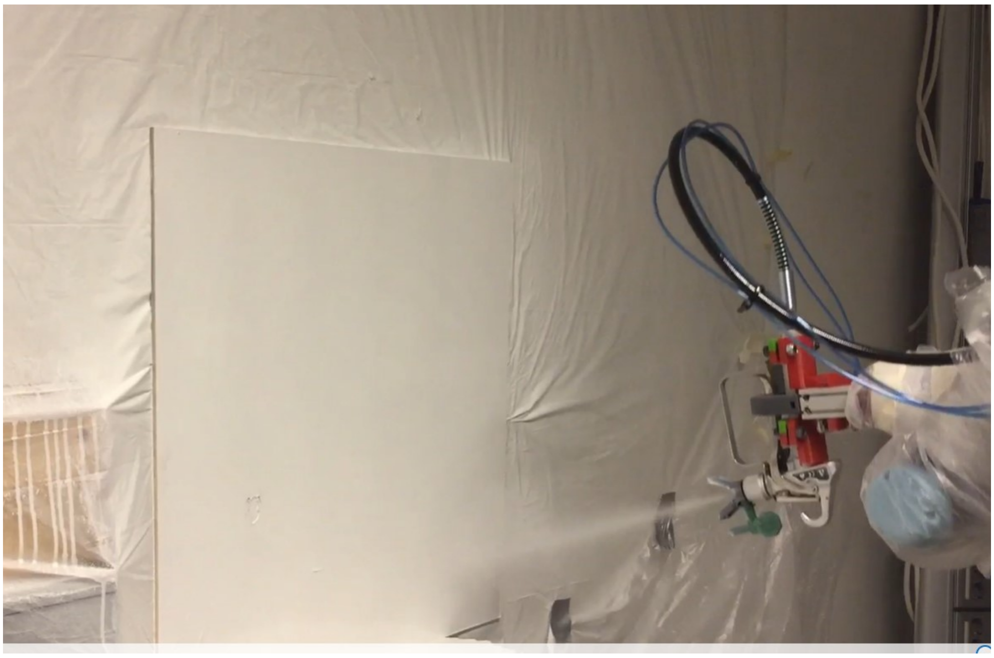
Figure 34. Setup for the test



15 Painting Results

The test yielded a smooth and a consistent painting results. Figure 35 presents the painting process and the result of painting. The process covered all areas that required painting accurately and precisely.

Figure 35. UR5e Robot painting process



16 DESIGN CHANGES

After the test the pneumatic actuator used in the end effector was changed to the electric actuator. This is because the pneumatic system depended on the air compressor whereas the electric actuator was independent of it, making system more compact.

16.1 FESTO Electric cylinder EPCE-TB

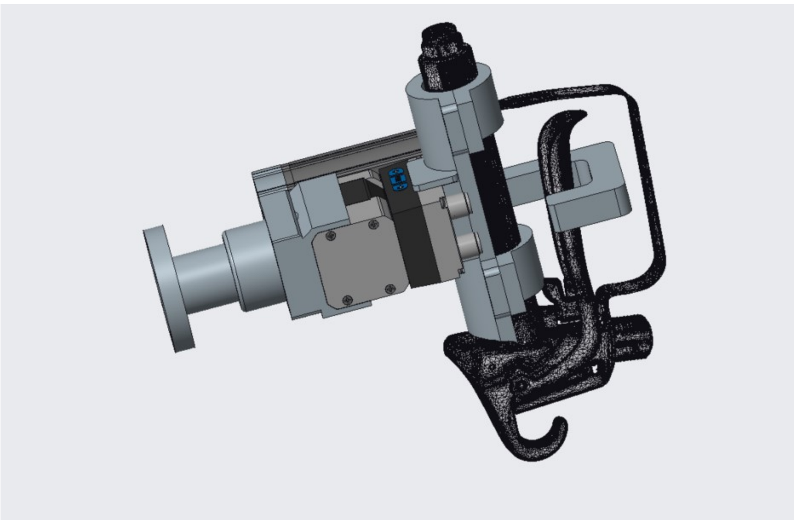
The compact electric linear actuator from FESTO was selected for the design with the stroke length of 20mm. Figure 37 shows the actuator. The maximum speed is 0.44m/s. The system is the complete solution with integrated compact cylinder, motor and controller. The actuator could be directly connected to the robot and can operate with 24V dc from the robot controller. Complete data sheet of the product can be seen in the Appendix (see Appendix 4) .

Figure 36. Electric Linear actuator from FESTO

16.2 Design of the New End Effector

A new end effector was designed. Figure 38 shows the setup of the new design. The design involved two main parts connected to the actuator, where one end could be connected to the wrist of the robot. The paint gun can be triggered when required using the J shaped component. The design uses the same clamping parts from the previous design.

Figure 37. New End Effector Setup



17 CONCLUSION

A complete painting system was designed at the end of the project. Moreover, a painting test was also performed inside HAMK’s robotics lab. The end effector and the holder required for the test were 3d printed. The result was a smooth and consistent painting operation. The result shows a good possibility in the application of the collaborative robot in the wall painting operation. The commissioning party were happy with the results achieved.

In the end, the project enhanced my skills in 3D modelling, offline programming and prototyping. Moreover, I learned about painting processes, types of paints and different painting equipment throughout the project. Similarly, I also gained experience in academic report writing and time management. I am looking forward to using the skills gained in my working career.

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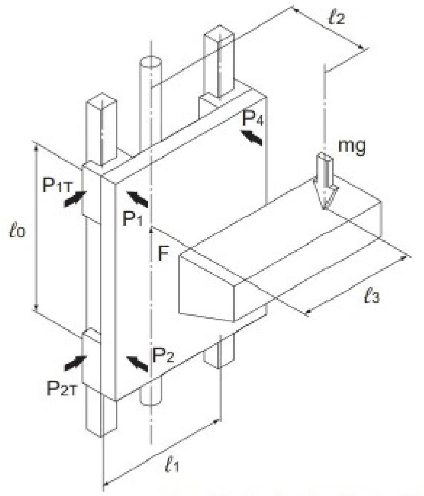
Appendix 1: Calculations of the linear guides

Vertical mount
Uniform motion or dwell



E.g.: Vertical axis of industrial robot, automatic coating machine, lifter

$$P_1 = P_4 = -\frac{mg \cdot \ell_2}{2 \cdot \ell_0}$$

$$P_2 = P_3 = \frac{mg \cdot \ell_2}{2 \cdot \ell_0}$$

$$P_{1T} = P_{4T} = \frac{mg \cdot \ell_3}{2 \cdot \ell_0}$$

$$P_{2T} = P_{3T} = -\frac{mg \cdot \ell_3}{2 \cdot \ell_0}$$

$M := 50 \cdot kg$

$l_2 := 140mm$

$l_0 := 150mm$

$l_3 := 10mm$

$P_{1T} = P_5$

$P_{2T} = P_6$

$P_{3T} = P_7$

$P_{4T} = P_8$

During Uniform motion

$$P_1 := -\frac{M \cdot g \cdot l_2}{2 \cdot l_0} = -228.822\,N$$

$$P_4 := P_1 = -228.822\,N$$

$$P_2 := \frac{M \cdot g \cdot l_2}{2 \cdot l_0} = 228.822\,N$$

$$P_3 := P_2 = 228.822\,\text{N}$$

$$P_5 := \frac{M \cdot g \cdot l_3}{2 \cdot l_0} = 16.344\,\text{N}$$

$$P_8 := P_5 = 16.344\,\text{N}$$

$$P_6 := -\frac{M \cdot g \cdot l_3}{2 \cdot l_0} = -16.344\,\text{N}$$

$$P_7 := P_6 = -16.344\,\text{N}$$

Equivalent Load Calculation

$$E := |P_1| + |P_5| = 245.166\,\text{N}$$

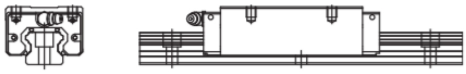
Safety Factor

$$C_0 := 3696\text{kgf}$$

$$S := \frac{C_0}{E}$$

$$S = 147.84$$

Appendix 2: TRH/TRS/TRC International Standard Linear guide



Model No.	Load Rating (kgf)		Static Permissible Moment					Weight	
			Mx (kgf-mm)	My (kgf-mm)		Mz (kgf-mm)		Block (kg)	Rail (kg/m)
	C	Co	Single Block	Single Block	Double Block	Single Block	Double Block		
TRH15VN	1206	2206	16,436	14,884	70,960	14,884	70,960	0.15	1.32
TRH15VL	1343	2574	19,175	20,429	95,224	20,429	95,224	0.22	
TRH20VN	2050	3696	37,334	33,268	157,298	33,268	157,298	0.31	2.28
TRH20VE	2553	5058	51,089	63,229	284,163	63,229	284,163	0.44	
TRH25VN	2581	4503	52,239	43,407	207,324	43,407	207,324	0.52	3.17
TRH25VE	3248	6255	72,554	85,112	391,311	85,112	391,311	0.77	
TRH30VN	3807	6483	90,722	74,970	355,321	74,970	355,321	0.85	4.54
TRH30VE	4791	9004	126,003	147,000	677,068	147,000	677,068	1.3	
TRH35VN	5090	8346	142,722	106,070	519,799	106,070	519,799	1.47	6.27
TRH35VE	6667	12274	209,885	233,977	1,070,533	233,977	1,070,533	2.26	
TRH45VL	7572	12808	292,657	220,751	1,030,183	220,751	1,030,183	3.00	10.4
TRH45VE	8852	16010	365,821	348,554	1,598,703	348,554	1,598,703	3.90	
TRH55VL	14703	21613	571,342	411,729	2,019,184	411,729	2,019,184	4.42	16.1
TRH55VE	17349	27377	723,699	670,530	3,148,637	670,530	3,148,637	5.50	
TRH65VL	22526	31486	973,074	695,840	3,594,277	695,840	3,594,277	8.66	22.54
TRH65VE	27895	42731	1,320,601	1,307,568	6,312,759	1,307,568	6,312,759	10.30	

A Linear Guide

Appendix 3: Program used for testing

```
BeforeStart
 Set DO[0]=Off
 Set DO[1]=Off
 Wait: 0.5
Robot Program
 x≔0
 Length≔0.8
 Breadth≔0.4
 cycle≔Length/0.4
 MoveJ
  Waypoint_1
 Loop x≤cycle
  x≔x+1
  Set DO[1]=On
  Wait: 0.2
  Set DO[1]=Off
  pos≔get_actual_tcp_pose()
  height_pos≔pose_trans(pos, p[0,(Breadth+0.01),0,0,0,0])
  MoveP
   height_pos
  Set DO[0]=On
  Wait: 1.0
  Set DO[0]=Off
  right≔pose_trans(height_pos, p[-150/1000,0,0,0,0,0])
  MoveL
   right
  downmotion≔pose_trans(right, p[0,-(Breadth+0.01),0,0,0,0])
  Set DO[1]=On
  Wait: 0.2
  Set DO[1]=Off
  MoveP
```

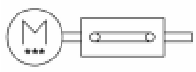
```
  downmotion
Set DO[0]=On
Wait: 0.2
Set DO[0]=Off
movepo≔pose_trans(downmotion, p[-150/1000,0,0,0,0,0])
MoveL

  Movepo
```

Appendix 4: Data Sheet of Electric cylinder unit

Electric cylinder unit
EPCE-TB-45-20-FL-ST-M-H1-PLK-AA

Part number: 8101540

FESTO



Data sheet

Feature	Value
KC characters	KC EMC
Shock resistance	Shock test with severity level 1 as per FN 942017-5 and EN 60068-2-27
Max. cable length	15 m outputs 15 m inputs 20 m for IO-Link® operation
Display	LED
Vibration resistance	Transport application test with severity level 1 as per FN 942017-4 and EN 60068-2-6
Logic input specification	Based on IEC 61131-2, type 1
Input switching logic	PNP (positive switching)
Ready status indication	LED
Parameterization interface	IO-Link® User interface
Additional functions	User interface Integrated end-position sensing
Characteristics of logic input	Configurable Not galvanically isolated
Note on ambient temperature	Above an ambient temperature of 30°C, the power must be reduced by 2% per K.
Switching logic at outputs	PNP (positive switching)
Logic interface, connection pattern	00992264
Power supply, connection pattern	00995989
Characteristics of digital logic outputs	Configurable Not galvanically isolated
Power supply, connection technology	M12x1, T-coded as per EN 61076-2-111
Logic interface, connection technology	M12x1, A-coded as per EN 61076-2-101
Power supply, type of connection	Plug
Logic interface, connection type	Plug
DC nominal voltage	24 V
Max. current of digital logic outputs	100 mA
Number of digital logic outputs 24 V DC	2
Number of digital logic inputs	2
Logic interface, number of poles/wires	8
Power supply, number of pins/wires	4
Product weight	833 g
Max. current consumption	3000 mA
Work range of logic input	24 V
Rotor position sensor resolution	16 bit

Feature	Value
Nominal current	3 A
IO-Link®, port class	A
IO-Link®, service data contents IN	32 bit force 32 bit position 32 bit speed
IO-Link®, SIO mode support	Yes
IO-Link®, process data width IN	2 Byte
IO-Link®, minimum cycle time	1 ms
IO-Link®, process data content IN	1 bit (state device) 1 bit (state move) 1 bit (state in) 1 bit (state out)
IO-Link®, process data width OUT	2 Byte
IO-Link®, protocol version	Device V 1.1
IO-Link®, number of ports	1
IO-Link®, process data content OUT	1 bit (move in) 1 bit (move out) 1 bit (quit error)
IO-Link®, communication mode	COM3 (230.4 kBd)
IO-Link®, data memory required	500 byte
Protection class	III
IO-Link®, Connection technology	Plug
Maintenance interval	Life-time lubrication
Toothed belt material	Polychloroprene with glass fiber
Toothed belt elongation	0.31 %
Toothed belt pitch	2 mm
Drive pinion effective diameter	10.18 mm
Feed constant	32 mm/U
Size	45
Stroke	20 mm
Stroke reserve	0 mm
Piston rod thread	M6
Type code	EPCE
Mounting position	Any
Piston rod end	External thread
Motor type	Stepper motor
Position sensing	Motor encoder
Design	Electric actuator with toothed belt With integrated drive
Symbol	00997342
Protection against torsion/guide	With plain-bearing guide
Homing	Fixed stop block positive Fixed stop block, negative
Rotor position sensor	Absolute encoder, single-turn
Rotor position sensor measuring principle	Magnetic
Max. acceleration	9 m/s²
Max. speed	0.44 m/s
Repetition accuracy	±0.05 mm
Duty cycle	100%
Insulation protection class	B
Permissible voltage fluctuations	+/- 15 %
CE marking (see declaration of conformity)	As per EU EMC directive As per EU RoHS directive
Corrosion resistance class (CRC)	0 - No corrosion stress
Storage temperature	-20 °C ... 60 °C

Feature	Value
Relative air humidity	0 - 90 %
Degree of protection	IP40
Ambient temperature	0 °C ... 50 °C
Certification	RCM compliance mark
Impact energy in the end positions	0.003 J
Max. torque Mx	0 Nm
Max. torque My	0.4 Nm
Max. torque Mz	0.4 Nm
Max. feed force Fx	85 N
Guide value for payload, horizontal	5 kg
Guide value for payload, vertical	2.5 kg
Reference value, running performance	200 km
Moving mass at 0 mm stroke	83 g
Additional weight per 10 mm stroke	29 g
Basic weight with 0 mm stroke	775 g
Additional moving mass per 10 mm stroke	0.455 g
Type of mounting	With internal thread With accessories
Note on materials	Contains paint-wetting impairment substances RoHS-compliant
Cover material	Wrought aluminum alloy, anodized
Housing material	Wrought aluminum alloy, anodized
Piston rod material	High-alloy stainless steel