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Remote Control Of A Hose For Concrete Pouring

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Foreword

Through cooperation between the Center for Construction Robotics and the companies Heidelberg Materials and Swerock, a SmartBuilt Environment project has been set up. The project focuses on tackling a commonly encountered safety concern regarding the pouring process for manufacturing concrete slabs which involves using a concrete pump truck. I would like to express a sincere thank you to all the mentioned stakeholders for setting up this project and providing me with the tools and the prototype necessary to conduct the research.
Furthermore, I would like to thank my supervisor Mathias Haage for arranging a suitable place in the Robot Lab, assisting in troubleshooting and getting the setup up and running. In addition, I would like to express my gratitude for his continuous guidance throughout the project, providing useful feedback and functioning as a valuable discussion partner. I would like to thank my deputy supervisor Björn Olofsson for helping me find out about the project and providing feedback during the final stages. Finally, I would like to thank my friends and family for expressing interest in my activities and supporting me throughout them.

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Ivo Hoffmanns

Abstract

The process of pouring concrete is very common in the construction industry. Typically, a person stands on top of reinforcements around the mold of the slab while manually pushing the hose, guiding it in a smooth side-to-side movement until an even pour has filled up the mold. Another person is positioned at a distance from the pouring end controlling the pump and thus the flow of concrete through the hose. The characteristics of the concrete and the flow add significant unpredictability to the process. The concrete is pumped through a long boom system of a pump truck and thus requires enormous pressures to reach the end. In addition, air bubbles occasionally will present themselves in the flow of concrete and these give rise to unexpected changes in the behavior of the pouring hose at the end, causing it to suddenly jerk or vibrate. This clearly poses safety risks for the operator. With a vision of removing this safety concern, a prototype has been built that allows the operator to control the pouring end of the hose remotely. This aim is translated into two research questions that are answered. ”Can the operator guiding the hose during the pouring of concrete be replaced by an operator controlling the hose remotely?” and ”Is a specific steering strategy optimal or preferred compared to another?”.
The prototype consists of an end hose that can be mounted to the end of a standard boom truck hose. By tactically controlling the length of four separate Pneumatic Muscle Actuators the hose can be moved in all directions. The prototype is set up in a lab and a range of tests is performed. A PLC is programmed to control the length of each muscle by changing the air pressure through pressure control valves using a remote controller, resulting in the movement of the hose. Two steering methods are tested in a final human-in-the-loop test that shows promising results for the prototype. Recommendations for improving the steering behavior are given and focus on ways to increase the airflow out of the muscles allowing the hose to move faster and smoother. Further tests and developments are required with the next milestone being a so-called ”wet-test” where the performance is assessed while concrete is pumped through the hose.

Keywords: Concrete pouring, Remote control, Pneumatic Muscle Actuator.

Abbreviations and Symbols

Abbreviations

Abbreviation	Definition
DC	Direct Current
DSDM	Dynamic Systems Development Method
HMI	Human Machine Interface
PLC	Programmable Logic Controller
PMA	Pneumatic Muscle Actuator
PSU	Power Supply Unit
ST	Structured Text
VPPM	Proportional Pressure Regulator
3D	Three-Dimensional

Symbols

Symbol	Definition	Unit
E	Young's Modulus	[N/m^2]
F	Force	[N]
h	Contraction	[%]
I	Moment of Inertia	[m^4]
K	Effective Length Factor	[-]
L	Length	[m]
M	Moment	[Nm]
P	Applied Load	[N]
P	Pressure	[bar], [mbar]
r	ratio	[-]
V	Voltage	[V]
v	Volume	[ml]
δ	Deflection	[m]

Contents

1 Introduction

Figure 1.1: Manual control of the concrete pouring hose on a typical construction site, image by Yuri Kim [1].

Concrete is a material that has widespread usage in the construction industry. The sheer size and volume of concrete structures call for efficient distribution and pouring processes. Large pumps and hoses are often required to move the concrete to its destination. This process commonly features two operators, one controlling the flow and another one controlling the placement of the concrete. A boom truck is typically used to move the pouring hose close to the structure that is to be filled with concrete. In order to distribute the concrete properly, however, an operator has to manually move the end piece of the hose that is suspended in the air from the boom as illustrated in Figure 1.1. The large diameter of the hose, combined with the long distances and heavy weight of the concrete necessitate high pressures ranging from 50 [bar] up to 400 [bar]. These high pressures can induce immense vibrations and shocks to the pouring end of the concrete hose. Air bubbles that get trapped in the concrete flow may violently exit the hose under such pressure, clearly posing important safety risks to the operator carrying the hose. Considering the fact that on construction sites the operators often are required to walk on reinforcements above the area in which the concrete has to be poured, stability can sometimes be problematic. This opens up a tremendous opportunity for robotics to take over manual labor-heavy activities and increase safety on construction sites, possibly increasing efficiency as a bonus. This opportunity was recognized and a prototype hose manipulator has been built with the goal of improving safety by having an operator remotely control the pouring end of the concrete hose. To determine the feasibility, this report aims to answer the main research question: ”Can the operator guiding the hose during the pouring of concrete be replaced by an operator controlling the hose remotely?” A secondary research question that can be answered is: ”Is a specific steering strategy optimal or preferred compared to another?”

The prototype consists of part of a hose that can be attached to the end of the concrete boom truck. A set of four pneumatic muscles run in parallel to the hose part, evenly spaced from each other, as can be seen in Figure 1.2. Pressurizing the muscles will shorten them, causing the hose to bend in that direction.

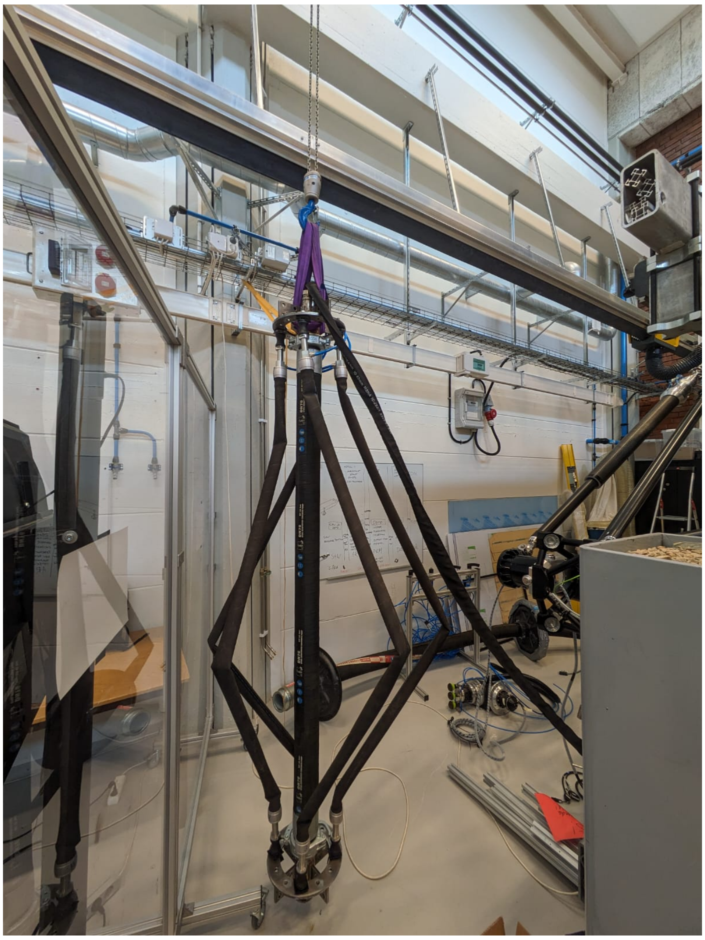


Figure 1.2: The prototype as set up in the lab.

The Methodology portion of the report starts out with a brief literature review in which general practices and developments in the world of construction robotics, and more specifically, the pouring of concrete are highlighted. Some examples are provided of robotic solutions discussing their uses and benefits. A more in-depth look into the use and control of pneumatic muscle actuators is provided, offering important background information concerning the driving mechanism of the prototype.

A detailed overview of the test setup and all relevant components of the prototype is given. Thereafter, following an iterative version of the dynamic systems development model (DSDM), the main functionalities of the setup are developed, tested, evaluated and where necessary, improved upon. Consequently, these are combined into a single functional program that controls the setup during a human-in-the-loop test, where the performance is assessed in a more realistic situation.

Finally, the report ends with a conclusion where the research questions are answered and an outlook, including recommendations for the future, is provided.

2 Literature Review

It is not a secret that the construction industry is full of labor-intensive work. Large-scale operations are commonly required for preparing, mixing, pouring, distributing and leveling of concrete in the construction of buildings, slabs, pools, floors and much more. Naturally, laborious work opens up an opportunity for technology to step in and take over parts of the job with the goal of increasing efficiency, safety and cost-effectiveness. An important factor to consider when deciding whether to use automated or semi-automated solutions or manual labor is the scale of the project. Robotics often require a large initial investment that must be justified by proving its worth in time saved or efficiency increases in performing a particular job. For robotic solutions, a trade-off has to be made between flexibility and efficiency as focusing on improving one aspect often negatively affects the other. For this reason, robotics might often be more suitable for larger-scale projects in which a process is very repetitive and time-consuming. Safety, however, is always a good driving factor for the development and interest in replacing manual labor [2].

There are currently multiple solutions on the market for automatic or remote-controlled pouring of concrete by different brands. One such solution is a motorized, 4-wheeled robot equipped with a concrete pouring hose produced by Somero Enterprises INC shown in Figure 2.1 [3]. The main concrete supply hose is to be connected to the vehicle, which can then be remotely controlled or programmed to drive around and pump out the concrete. This solution takes over the need to manually move the concrete supply hose and can efficiently distribute the concrete. Multiple robots can be used simultaneously focusing on guidance and positioning of the supply line when pouring large surfaces. Applications of the robots are somewhat limited to pours consisting of large flat surfaces such as floors, as these robots require a flat surface, often the reinforcements, to drive over.

Another type of device is the so-called ”shotcrete” robot, shown in Figure 2.2. This piece of machinery is used for automated or semi-automated spraying of concrete, often applied in the construction of tunnels and for reinforcement of walls during excavations. This device typically consists of a stationary part in which a partial mix is prepared and held after which it is pumped through a hose where, depending on the application, sand, fibers or other reinforcing materials are mixed in with the flowing concrete. It is then extruded at high velocities, spraying it onto the target surface. Shotcrete can be very useful for applying layers of concrete on surfaces. There exist different types of solutions, some require manual control of the spraying end and some can be remotely controlled. Depending on the type of shotcrete, dry versus wet, remote-controlled can be preferred as dry shotcrete releases harmful dust and other air pollutants. This solution can therefore seriously mitigate safety risks [4].

Figure 2.1: The SP16 from Somero Enterprises INC is a remote-controlled robot capable of efficiently positioning the supply hose and pouring the concrete [3].

Figure 2.2: Example of an automated shotcrete robot, image by MTA Construction & Development Mega Projects [5].

A third type of concrete pouring robot that is used, is the cantilever pouring robot such as the one shown in Figure 2.3. This kind of device can be truck-mounted or standalone and consists of a series of hydraulically actuated members that can fold out to reach distances far away from the truck or concrete supply. Depending on the type of boom pump, pouring at a height or reaching over an obstacle such as a wall is made possible. In many cases, however, the flexible end hose of these boom pumps still needs to be manually controlled by an operator. Large movements of the end hose can be made by remotely controlling the sections of the boom pump. These kinds of movements are common when moving between areas of a larger surface that is being poured. The concrete is distributed within a smaller area by manually moving the end hose, but this area is limited by the range of the pouring end. A larger motion is then required to move the hose to a new area where the concrete can be distributed by hand again. The mechanical characteristics of such a boom pump make it difficult to accurately determine the position of the end hose. The boom is built up of a number of cantilever beams placed in series. These members cannot be considered infinitely stiff bodies but rather show significant elastic deflection. A lightweight design of the boom is desired for multiple reasons such as savings in cost and energy requirements for the system. A reduction of the weight of each member brings in more deflection and increases the likelihood for vibrations to appear, in turn, decreasing the accuracy of the position of the end hose even more. Whether this type of concrete pouring process is suitable for automation depends of course on the size or range of the boom but also on the accuracy requirements of the area that is to be poured [6].

Figure 2.3: Example of a concrete boom truck type of device used to pour concrete, image by Joseph J. Albanese [7].

Figure 2.4: Prototype that achieves an automated tendon-driven motion of a flexible concrete house used for additive manufacturing, developed at Clemson University [8].

When looking for solutions that focus more on accurate pouring or rather deposition of concrete, the step to 3D printing is quickly made. Several types of solutions are being developed with the aim of taking advantage of the typical benefits that additive manufacturing brings to the table such as accuracy, the option to create relatively complex shapes, and of course, allow for rapid prototyping. Although there is a lot of research being performed in this area, the main limitation is finding viable materials. In order to be suitable for 3D printing, materials need to have certain flow characteristics which is often not the case for the common types of concrete used in construction. Types of robots that facilitate the deposition of the concrete include robot arm-like manipulators, where the concrete extruder is mounted on a typical robot arm. Other types are basically scaled-up versions of regular 3D printers where the extruder moves along guides using linear motors which allows the printer to fill up a specific area [9]. A specific solution that focuses on controlling the end hose of a concrete supply hose is shown in Figure 2.4. This is a prototype developed at Clemson University that creates targeted movements of the hose by tensioning tendons that run alongside the hose. This principle could be used to remove the operator from the direct area where the concrete is to be poured [8].

3 The Pneumatic Muscle Actuator

Pneumatic Muscle Actuators (PMA) have been around since the 1950's finding their main use in prosthetics, although quickly being replaced by electric motors. The advantages of pneumatics, being very cost-effective and yielding a high power-to-weight ratio compared to competitors, are often overshadowed by the drawbacks. The compressibility of air raises difficulties in controlling the exact output position of the end-effector, especially under varying loads by showing a spring-like effect. Moreover, significant changes in behavior can be observed when comparing a ”cold” muscle with a ”warm” muscle, so prolonged use will show different results from intermittent use [10].

The prototype hose manipulator for this project uses the pneumatic muscle actuators in a rather unconventional manner. The strengths of PMA are mainly found in short-stroke applications. When using them through their full range of motion, traditionally up to a contraction of 25% of their original length, the force that can be delivered drops quickly to near 0[N]. In addition to this, hysteresis decreases the precision of the final, equilibrium position of the actuator, thus reducing its reproducibility, which is in many applications detrimental [11]. What makes the PMA still useful for the application is that accurate positioning is not strictly necessary. The experiments will always be done with a certain form of feedback. This feedback is provided by the operator looking at how the concrete pouring hose is moving, but could in the future be replaced by a sensor to improve the control feedback loop.

3.1 Physics behind the movement

Before actually moving the hose, it is important to consider how movement is generated. In a simplified model, the concrete hose itself can be viewed as a cylinder that experiences a compressive force, a bending force, and due to the way in which the muscles are attached, a moment from each pneumatic muscle when it starts to contract. The effects of the compressive force can be determined using the Euler-Buckling formula given in Equation 3.3. The effects of the bending force are approximated by using the equation for a point load on the free end of a cylinder that is fixed at the other end as shown by Equation 3.1. The deflection due to the moment can be calculated using Equation 3.2

$$\delta = \frac{P \cdot L^3}{3 \cdot E \cdot I} \tag{3.1}$$

Where P is the point load [N] applied at the end, L is the length [m] of the cylinder, E is the Young's Modulus [N/m^2] and I is the moment of inertia [m^4].

$$\delta = \frac{-M_0 \cdot x^2}{2E \cdot I} \tag{3.2}$$

Where M_0 is the moment applied to the free end in [Nm], x is the length of the cylinder in [m], E is the Young's Modulus in $[N/m^2]$ and I is the moment of inertia in $[m^4]$.

$$\delta = \frac{P_{applied} \cdot K \cdot L}{\pi^2 \cdot E \cdot I} \tag{3.3}$$

Where P is the applied load [N], K is the effective length factor [-], E is the Young's modulus $[N/m^2]$ and I is the moment of inertia $[m^4]$.
The pneumatic muscle exerts a force at an angle. When the hose has not moved and the muscle starts to contract, the force acts in compression or buckling and a moment around the end point of the hose. As the deflection increases, the angle between the muscle and the hose increases from zero and the portion of the force that applies a bending force on the end increases while the portion of the force that acts as a moment decreases.

3.1.1 Problems with predicting the end position

To determine the length of a muscle and the position of the hose end for a particular pressure value, a few problems arise. The main problem is the fact that the situation does not satisfy all the assumptions made that validate the use of the Euler-Bernoulli Beam Theorem. The deflection cannot be considered smaller than one-tenth of the beam length, which in turn means that the total deflection cannot be calculated by simple summation of the individual contributions to the deflection [12]. Combining this with some practical limitations such as unknown property values of the concrete hose material and the fact that the concrete hose has a slight curvature at rest, meaning it will behave differently depending on in which direction it bends, makes predicting the position even less accurate.
As discussed at the start of this section, the behavior of air muscles is highly non-linear and difficult to control. What this means in practice is that due to the friction between the strands in the air muscle among other factors, hysteresis can be noticed, leading to different possible equilibrium positions, depending on the path it took to get to the specific end position. Although the force that an air muscle can deliver at a certain length for a specific pressure value is provided by FESTO, as shown in Figure 3.1, attempting to accurately predict the end position from given pressure values is deemed too complex and not necessary. In the current vision, any experiment will contain a visual feedback loop, namely the operator will be directly looking at the robot while controlling it remotely and making real-time adjustments based on what is happening.

Figure 3.2 is a 3D plot of Figure 3.1 and visualizes the characteristics in a better way. The pressure will be given as input from the control. Starting out at 0% contraction, a force starts working to decrease the length of the muscle. The force required to decrease the length increases and the movement reaches an equilibrium once the available force matches the required force. Increasing the pressure now increases the available force which causes the contraction to increase until it again balances out the required force.

So although this data is not used for calculating the end position, it can be consulted when determining the optimal distance between both ends of a muscle. With the initial length of the PMA and the distance between the mounting points, the lower limit of contraction corresponding to the operating range of the prototype can be calculated.

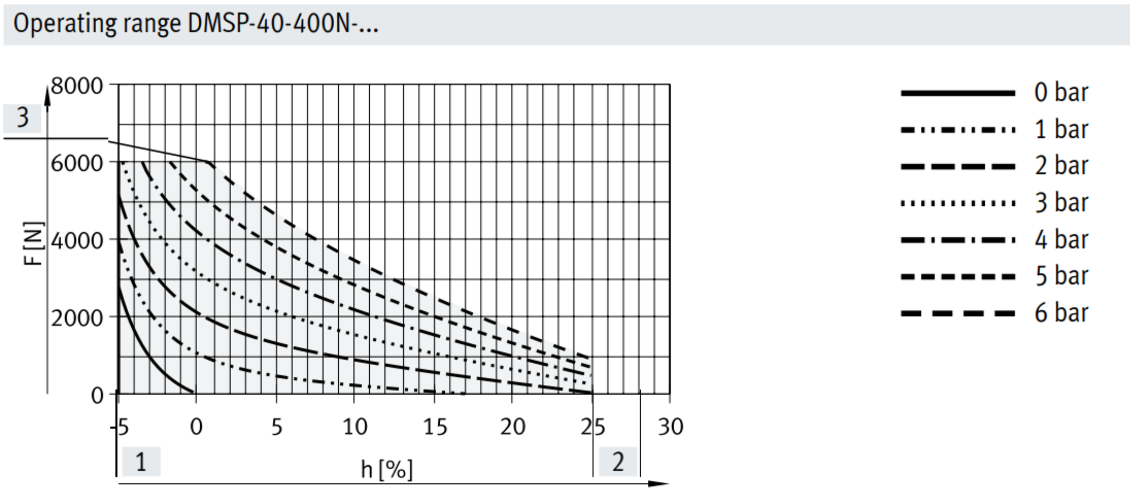


Figure 3.1: Force as a function of contraction for different pressure values [13].

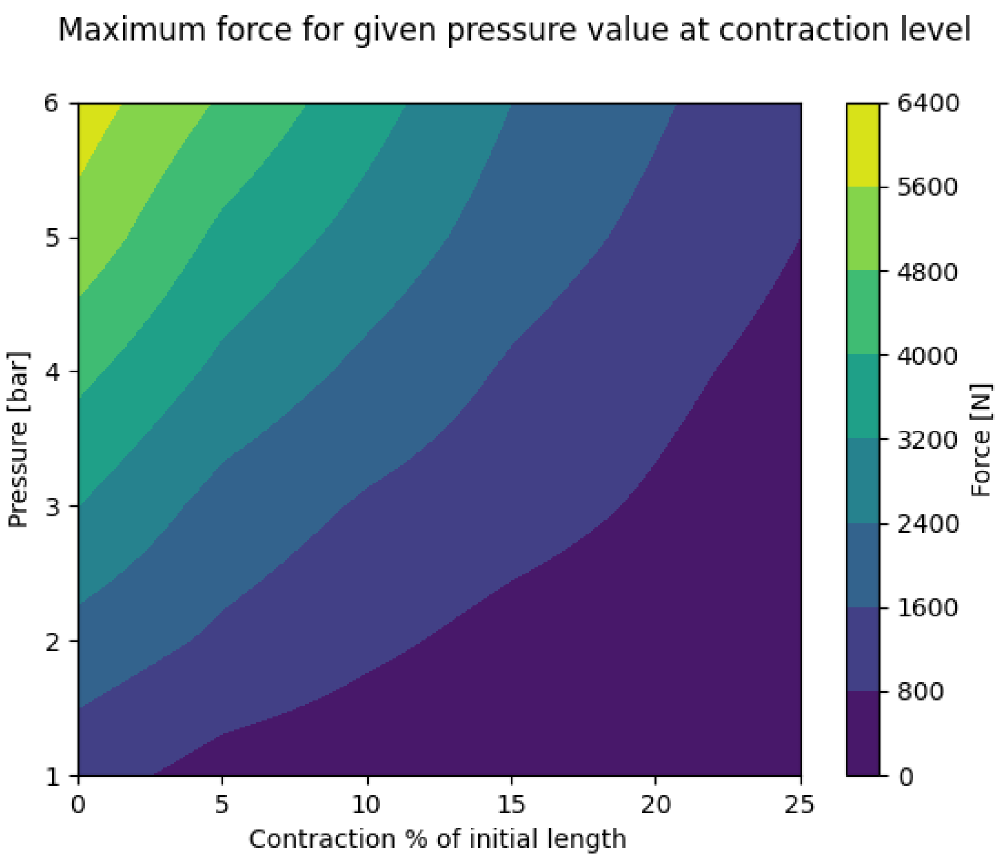


Figure 3.2: Interpolation grid. Pressure on the y-axis, contraction on the x-axis and the force on the color-axis.

4 Setup

To determine whether the prototype could offer a valid solution to the safety issue described in chapter 1, the option to safely perform tests with the prototype is required. A space in the lab is reserved where the device is suspended in the air, hanging from a hook. The hook is part of an overhead crane that spans across the ceiling and can be used for lifting and moving heavy objects. Since the hook is lowered a couple of meters from the ceiling, the top part of the prototype is fixed to a stiff structure in order to avoid large oscillations originating from the cable attached to the overhead crane. The area in which the hose can move is shielded by see-through walls to avoid any person being hit by the hose. All other components are fixed to a table at a safe distance from the prototype.

4.1 Prototype

The hose manipulator consists of a piece of steel-reinforced tubing from IVG Colbachini S.P.A, an Italian manufacturer that specializes in producing tubes for pumping, amongst concrete, many other liquids, gasses and granulates. A steel disc is attached to each end of the tube using a connection piece that allows for the mounting on a standard concrete boom truck hose. The steel plates contain four holes through which the pneumatic muscles are attached with a nut and bolt connection and a flexible joint. The muscles are evenly spaced and run parallel to the hose, as shown in Figure 4.1.

Figure 4.1: Top part of the prototype, highlighting the mounting points of the air muscles.

The initial length of the muscles is two meters and the distance between both ends is 1.75 meters, which means a contraction of 12.5% is required before any movement occurs. By decreasing the length of one or more of the air muscles while keeping the lengths of the others the same, the hose will bend toward that direction.

4.2 Pneumatics

All pneumatic equipment is manufactured by Festo, a well-established supplier of pneumatic and automation equipment all over the world.

4.2.1 Service Unit

To ensure the system works as expected and the lifetime of the components in the system is maximized, an air service unit is connected to the facility air. The service unit consists of the following components in downstream order:

- A manual On/Off valve.
- A filter manual regulator.
- A fine filter.
- A soft start/ quick exhaust valve.

4.2.2 Proportional Pressure Control Valve

The valve manifold contains four proportional pressure control valves (VPPM). These regulators contain a nitrile rubber diaphragm that separates an actuator and the airflow. The diaphragm balances the forces from the air pressure on one side and the actuator forces on the other. A valve plug, connected to the diaphragm controls how much air flows through the valve. If the downstream pressure increases, the diaphragm moves upwards, decreasing the orifice size, which decreases the pressure and vice versa. The desired pressure determines how much force the actuator exerts on the diaphragm and any changes in the demand increase or decrease the pressure which moves the valve plug up or down to counterbalance these effects. Figure 4.2 shows a schematic of a typical spring-actuated diaphragm pressure regulator.

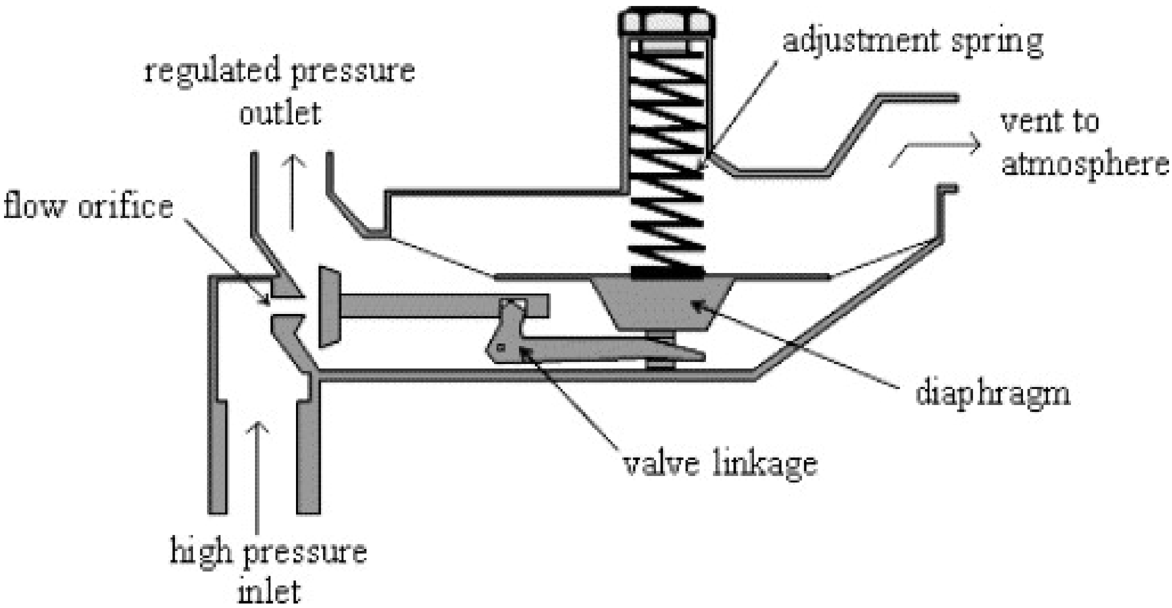


Figure 4.2: Schematic of a standard spring actuated diaphragm pressure regulator valve.[14]

The VPPM has a built-in multi-sensor cascade control loop that tries to minimize the error between the setpoint and the actual pressure of the working volume. The sensor measures the current, actual pressure continuously and through codesys both the setpoint and the actual pressure can be read in real-time. The VPPM has three different control parameter sets that can be used. Parameter set three is recommended for applications with a tube length ≥ 5[m] and an output volume > 2000 [ml], which is the case in this setup [15].

The air is then connected to the supply port of the manifold block in the valve terminal and split five ways to supply air in parallel to the four proportional pressure regulators. The output of each proportional pressure regulator is connected to one pneumatic muscle of the hose manipulator. A simple schematic of the setup is shown in Figure 4.3. A technical schematic of the pneumatics can be found in Appendix A. The control part of the setup in the lab is shown in Figure 4.4

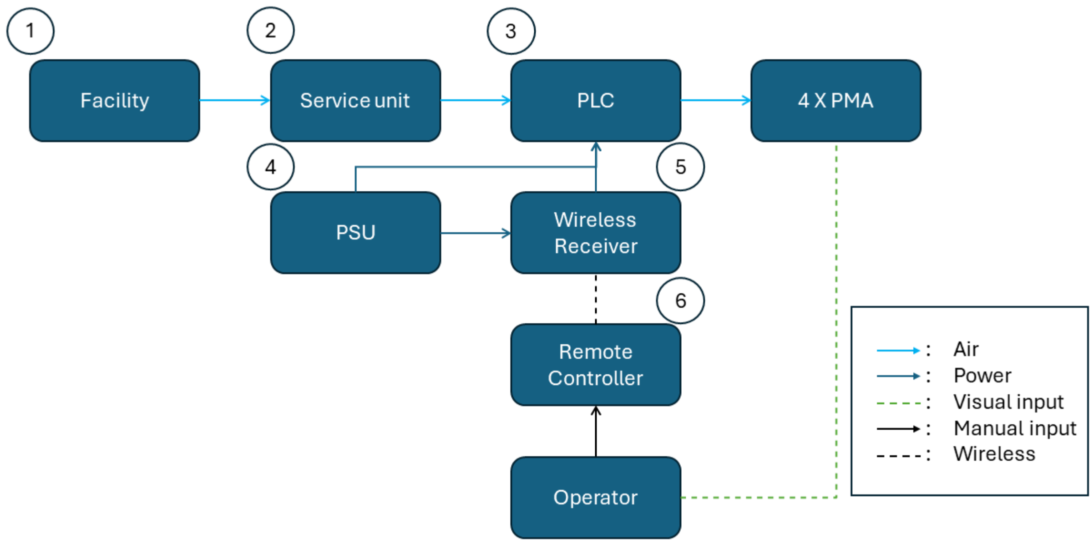


Figure 4.3: A simple representation of the setup showing the different types of communication present.

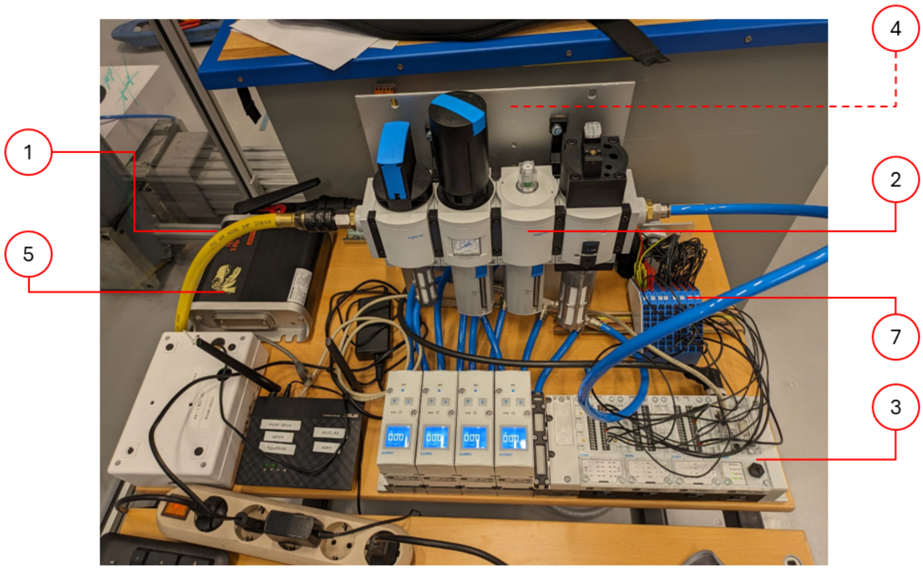


Figure 4.4: The control part of the setup.
(1): The connection to the facility air input.
(2): The service unit.
(3): The PLC, CPX terminal with the digital input/output module, two analog input modules and four VPPM proportional pressure control valve modules.
(4): The power supply unit, located behind the service unit.
(5): The wireless receiver.
(6): The remote controller (not shown in this image), refer to Figure 4.8.
(7): The potential distribution terminal block.

4.3 Electronics

4.3.1 PLC

The valve terminal consists of two analog input modules with 4 analog inputs each and one digital input/output module with eight digital inputs and eight digital outputs. Figure 4.5 and Figure 4.7 show the pin allocation of the analog input module and the digital input/output module. Figure 4.6 can be consulted for clarification of the abbreviations used. By default, the analog inputs are not connected. When programming the PLC, each port should be manually configured through Codesys to allow a certain input method. Since the analog joystick outputs positive voltage values, the corresponding input method is selected from a drop-down menu.

X1.0: $24\ V_{SEN}$	X5.0: $24\ V_{SEN}$
X1.1: $0\ V_{SEN}$	X5.1: $0\ V_{SEN}$
X1.2: Input 0–	X5.2: Input 2–
X1.3: FE	X5.3: FE
X2.0: n.c.	X6.0: n.c.
X2.1: n.c.	X6.1: n.c.
X2.2: Input 0+	X6.2: Input 2+
X2.3: FE	X6.3: FE
X3.0: $24\ V_{SEN}$	X7.0: $24\ V_{SEN}$
X3.1: $0\ V_{SEN}$	X7.1: $0\ V_{SEN}$
X3.2: Input 1–	X7.2: Input 3–
X3.3: FE	X7.3: FE
X4.0: n.c.	X8.0: n.c.
X4.1: n.c.	X8.1: n.c.
X4.2: Input 1+	X8.2: Input 3+
X4.3: FE	X8.3: FE

Figure 4.5: Pin allocation for both analog input modules, obtained from the official FESTO datasheets [16].

Abkürzungen/ Abbreviations/ Abreviaciones/ Abréviations/ Abbreviazioni/ Förkortningar	de	en
$24\ V_{EL/SEN}$	Betriebsspannung Elektronik / Sensoren	Operating voltage for the electronics and sensors
$24\ V_{OUT}$	Lastspannung digitale Ausgänge	Load voltage for digital outputs
$24\ V_{VAL}$	Lastspannung Ventile	Load voltage for valves
Ix	Eingang x	Input x
Ox	Ausgang x	Output x
FE	Funktionserde	Functional earth
Housing	Gehäuse	Housing
n.c.	nicht verbunden	not connected

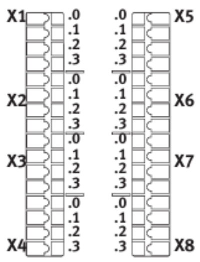
Figure 4.6: Clarification for the abbreviations used in the datasheets [16].

Terminal CPX

Data sheet – Input/output module, digital

Pin allocation	
Connection block inputs/outputs	CPX-8DE-8DA

CPX-AB-8-KL-4POL



X1.0: $24\ V_{SEN}$	X5.0: Output x+4
X1.1: $0\ V_{SEN}$	X5.1: $0\ V_{OUT}$
X1.2: Input x	X5.2: Output x
X1.3: FE	X5.3: FE
X2.0: Input x+4	X6.0: Output x+5
X2.1: Input x+5	X6.1: $0\ V_{OUT}$
X2.2: Input x+1	X6.2: Output x+1
X2.3: FE	X6.3: FE
X3.0: $24\ V_{SEN}$	X7.0: Output x+6
X3.1: $0\ V_{SEN}$	X7.1: $0\ V_{OUT}$
X3.2: Input x+2	X7.2: Output x+2
X3.3: FE	X7.3: FE
X4.0: Input x+6	X8.0: Output x+7
X4.1: Input x+7	X8.1: $0\ V_{OUT}$
X4.2: Input x+3	X8.2: Output x+3
X4.3: FE	X8.3: FE

Figure 4.7: The pin allocation for the digital input and digital output module, obtained from the official FESTO datasheets [16].

4.3.2 Remote controller and receiver

The controller and wireless receiver combination that is used in this setup is the Remotus T-Rx 1500 and the Era 100 JD from Åkerströms. Figure 4.8 shows the interface of the remote controller. The wireless receiver accepts commands through a cable composed of 41 individual wires, each with different functions such as providing power to the receiver, transmitting the state of buttons, outputting the voltage that corresponds to the position of the joysticks, etc. For a complete overview of what the function of each wire is, the wiring diagram can be found in Appendix A Figure A.2 and Figure A.3

Figure 4.8: (6): Remote controller interface consisting of two joysticks, four programmable buttons and one button to initiate the wireless connection.

4.3.3 Power supply and terminal block

A 24 [V] DC power supply unit (PSU) powers the valve terminal and all other components through a connection block. A potential distribution terminal block, PPV8 from Weidmüller connects all 41 wires, in order, to the corresponding channel. One row with 8 inputs is connected to ground and another row of 8 inputs is connected to the 24 [V] DC output of the PSU.
A Windows computer is available to connect to the router which in turn is connected to the PLC in order to program it. The valve terminal can thus be controlled remotely through Codesys.

5 Tests

To avoid trying to solve the entire problem at once, the development of the program that controls the prototype is divided into smaller steps or, as referred to in the rest of the report, specific tests. A variation of the dynamic systems development method (DSDM) is used through this phase of the project, as the capabilities of the program are iteratively expanded upon [17]. To start off, the functionality of all hardware is split up into smaller tests to ensure each component functions properly by itself. Codesys V3.5 SP19 Patch 5 is used in combination with IEC-61131-3, the standard for PLC programming.

5.1 Methodology

Each test has a certain goal of meeting a requirement of the desired final functionality of the system. For each test, a new program is written after which it is tested using the setup and then the results are carefully evaluated. If necessary, the code is updated, tested and evaluated again. Relevant findings are described and their effects are discussed. This process of updating, testing and evaluating the code is iterated until the results are satisfactory for that specific part. The tests gradually become closer to a real setting and functionalities achieved in previous tests may be implemented in the tests that follow. All tests lead up to a final human-in-the-loop test, where the performance of a remote-controlled concrete pour is evaluated and compared to the usual process where a human manually controls the pouring end of the hose. In Figure 5.1 a graphical representation of the subdivision of the tasks can be found. As visualized, some tasks are performed in parallel and others require certain tasks to be completed before being developed.

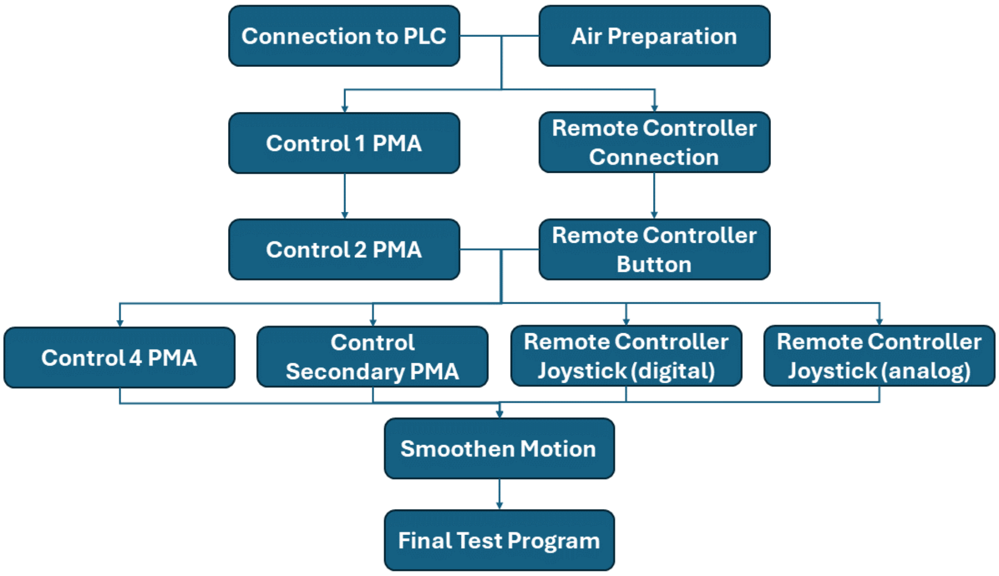


Figure 5.1: Graphical representation of the workflow for the subdivision of the tests.

5.2 PLC connection

For the first test, the manual for installing and commissioning the Festo CPX-CEC control block is followed [18]. This includes installing the Codesys V3.5 SP19 provided by Festo software and downloading the correct libraries for the CPX-CEC-S1-V3 PLC. Connection to the gateway from the computer and connection between the gateway and the PLC is established and the exact configuration of the PLC is read directly through Codesys. All components, the inputs, outputs and the proportional pressure control valves are checked to be active/running.

5.3 Air preparation setup

The goal of this test is to make sure all the individual components of the air service unit function as expected and the air reaches the valve terminal. This includes the following actions:

- Facility air is connected to the input of the service unit where the manual On/Off valve is located.
- The On/Off valve is manually turned to allow airflow from 1 to 2.
- The manual pressure regulator unit is tested by twisting the top part, thus internally decreasing the pressure to the desired level, 2.5 [bar] in this case.
- The next module is the finer filter unit. The air passes through by default.

- The final unit is the soft start/quick exhaust valve. It can be electrically opened by connecting a cable to the top. Since this cable was not available, the valve will be opened by pressing the manual override button.

5.4 One air muscle

One pneumatic muscle is connected to the output of the first proportional pressure control valve (VPPM-0). The input of the VPPM-0 and the input of the valve manifold block are connected to the 2.5 [bar] output of the air preparation unit. A simple Codesys program written in Structured Text (ST) combined with an HMI is used to monitor both the pressure setpoint and the current pressure in the pneumatic muscle. Using a button or a slider in the Codesys visualization, the setpoint can be adjusted. A trace object is added to the application that tracks both the actual pressure and the pressure setpoint values over time and plots them in real time. This data is exported to a text file and later plotted in Matlab to be further analyzed. As mentioned in the manual, the VPPM has three different control parameter settings referred to as sets one, two and three. Set one is characterized as fast control, set two as universal control and set three as precise control. Although set three is recommended considering the system characteristics, as part of this test, the different responses are analyzed. The test consists of a simple step function from 800-6000 [mbar] and a step function from 6000-800 [mbar].

5.4.1 Intermediate Results

The results are shown in Figure 5.2 and Figure 5.3. It becomes clear that all three sets give very similar responses, crossing the setpoint roughly at the same time. When zoomed in on the overshoot, set one reaches the setpoint around 0.2 seconds quicker compared to the others. From this, the conclusion is drawn that set1 is the best control parameter set to use, although any set would function.

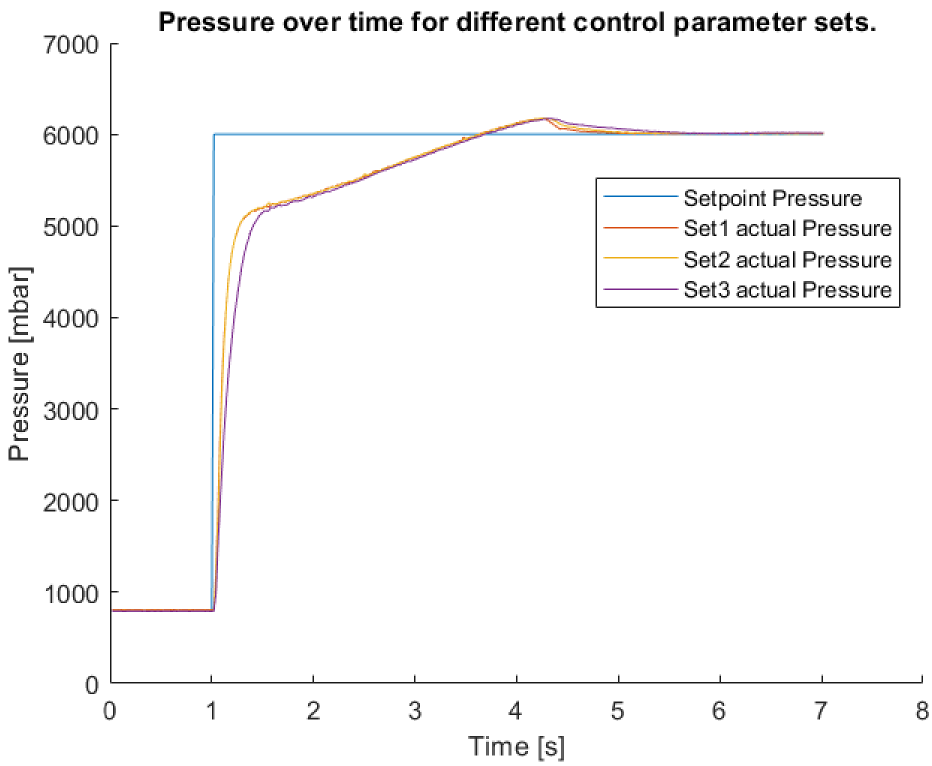


Figure 5.2: Positive step function for one muscle for different control parameter sets

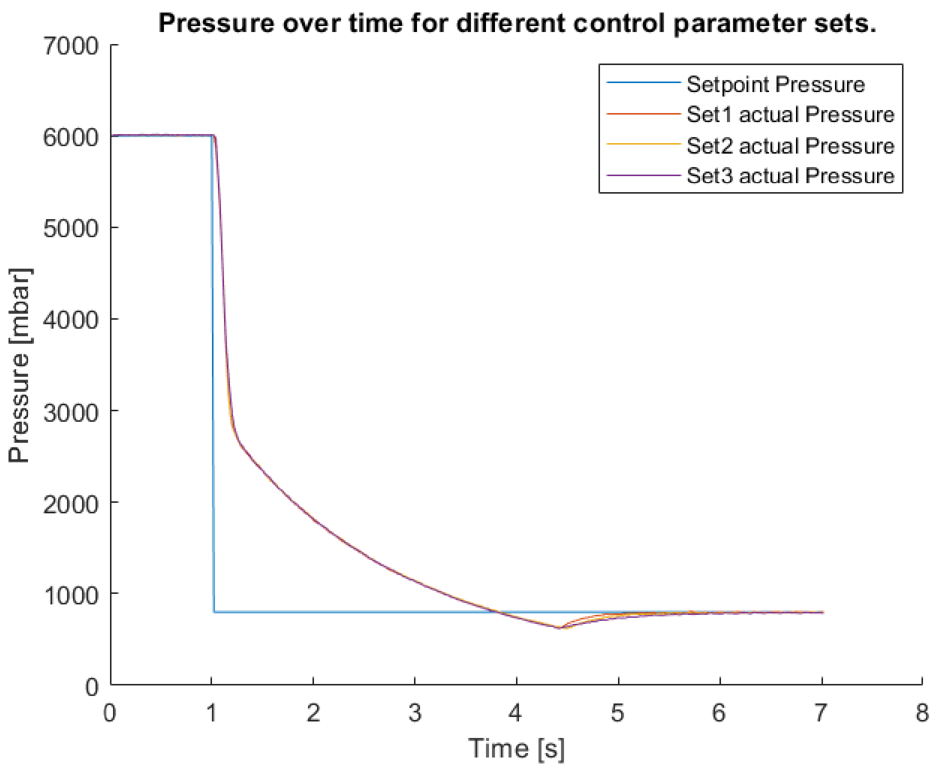


Figure 5.3: Negative step function for one muscle for different control parameter sets

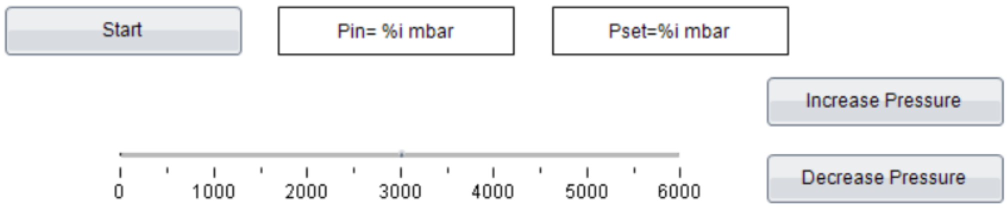


Figure 5.4: Simple HMI used for the one air muscle test.

```
PROGRAM PLC_PRG
VAR
    Plin AT %IW10:UINT;
    Plout AT %QW1:UINT;
    Start:BOOL:=FALSE;
    Pup:BOOL:=FALSE;
    Pdown:BOOL:=FALSE;

IF Start=TRUE THEN
    IF Pup=TRUE THEN
        Plout:= Plout+1;
    ELSIF Pdown=TRUE THEN
        Plout:= Plout-1;
    END_IF
END_IF
```

Figure 5.5: Structured Text code used to perform one air muscle test.

5.5 Two air muscles

For the two air muscle test, the output of the third proportional pressure valve is connected to the antagonistic pneumatic muscle such that a back-and-forth, planar motion can be observed.
The HMI, shown in Figure 5.6, is similar to the one used before but updated with a second slider for manually adjusting the pressure.

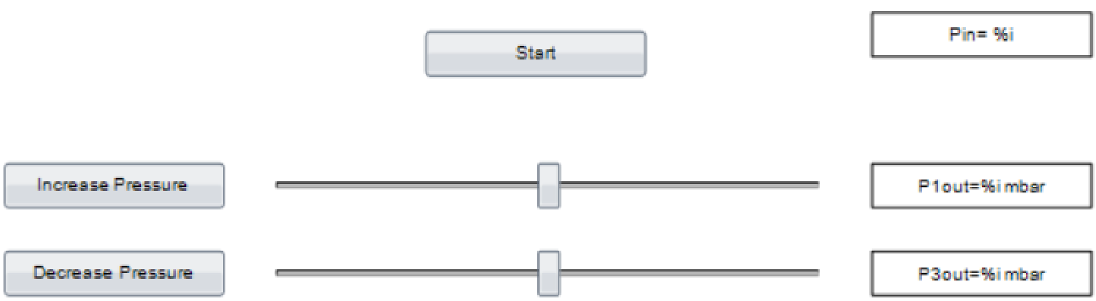


Figure 5.6: HMI for the two muscle test.

To ensure both muscles do not contract at the same time a piece of code is written in such a way that when the signal is given to move in one direction, the pressure in the antagonistic muscle is first reduced to a minimum value before the pressure in the muscle corresponding to the desired movement direction is increased. This movement pattern is achieved in both directions with the code shown in Figure 5.7.

```
PROGRAM PLC_PRG
VAR
    Plin AT %IW10:UINT;
    Plout AT %QW1:UINT;
    P3out AT %QW2:UINT;
    P3in AT %IW11:UINT;

```

```
IF Start=TRUE THEN
    IF Pup=TRUE AND P3in<=pmin AND Plout<pmax THEN
        Plout:= Plout+increment_Up;
    ELSIF Pup=TRUE AND P3in>=pmin THEN
        P3out:= P3out-increment_Down;
    ELSIF Pdown=TRUE AND Plin<=pmin AND P3out<pmax THEN
        P3out:= P3out+increment_Up;
    ELSIF Pdown=TRUE AND Plin>=pmin THEN
        Plout:=Plout-increment_Down;
    END_IF
END_IF
```

Figure 5.7: Code for moving back and forth in a plane using 2 muscles.

5.5.1 Intermediate Results

While playing around with the code and changing the value by which the pressure setpoint is incremented and decremented, a problem is noticed when using larger increments. When decreasing the pressure quickly, going through the zero-point where the hose is pointing straight downwards with low pressure values in both muscles and then changing direction and increasing the pressure in the opposite muscle, the phenomenon shown in Figure 5.8 and Figure 5.9 is observed. The length of the muscle increases at varying rates. When the pressure decreases from a high value to zero, the muscle lengthens at decreasing speeds, even though the pressure is dropping at similar rates. What this means is that the flow rate of air out of the muscle decreases with decreasing pressure. One explanation for this is the mechanism by which the air is pushed out of the muscle. On one hand, there is ambient pressure which is constant, but on the other hand, there is the act of the concrete hose pulling the muscle apart. The force at which the muscle is pulled apart is much higher at large deflection which corresponds to high pressure values. This force is partly due to gravity and partly due to the stiffness of the concrete hose.

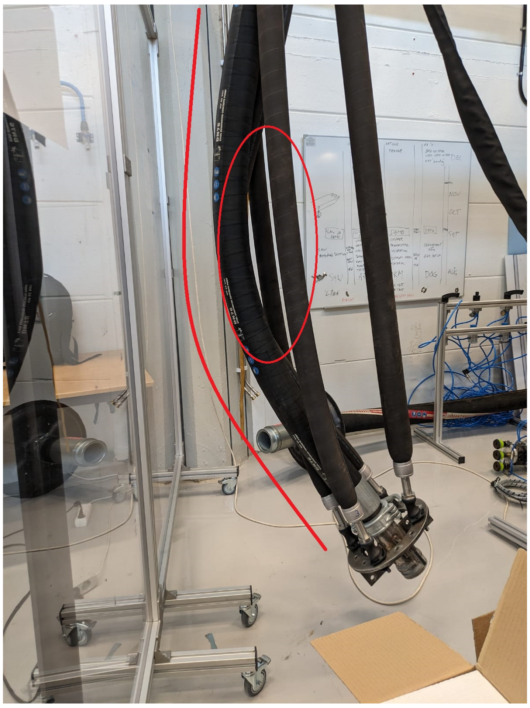


Figure 5.8: Image of the problem where the opposite muscle is still lengthening while the other muscle contracts already.

Figure 5.9: What the movement should look like.

To prove that the flow rate is the limiting factor and not the proportional pressure valve, the setpoint and actual pressure are automatically measured in codesys using a trace. This data is exported and plotted in Matlab. The plot in Figure 5.10 shows that the pressure is not the limiting factor as the setpoint is reached within two seconds, while in reality, it takes the muscle between 5-6 seconds to reach its equilibrium length.

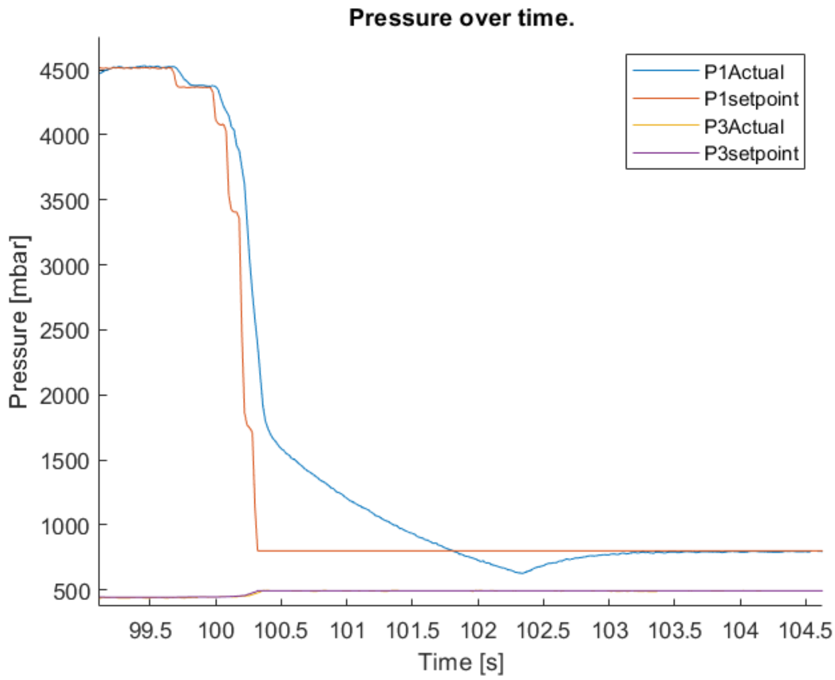


Figure 5.10: This plot shows the actual pressure and the setpoint. As can be seen it takes less than two seconds for the actual pressure to reach the setpoint.

5.6 Remote controller one button

To test whether the connection between the remote controller and the plc is correctly established or not, first, a single button is tested. Wire number fifteen from the wireless receiver, which corresponds to button number two on the controller, is connected to input one of the digital input/output module of the plc. A simple light is added to the HMI of the two air muscles test that lights up when the input is TRUE, meaning the button is pressed. Wire numbers 1, 2, 3 and 31 are connected to the 24 [V] DC input and 32 is connected to ground according to the functional diagram shown in Figure A.2 and Figure A.3.

Figure 5.11: HMI for the one button test.

5.7 Remote controller joystick with two air muscles

The connection between the remote controller and the PLC has been established by the test in section 5.6. The next step is to control the air muscles using the joystick. The digital outputs of the remote controller that correspond to the joystick being moved forward and backward are connected to two of the available digital inputs of the PLC. Similar to the method from section 5.5, these digital inputs now replace the variables Pup and Pdown in the code, and function in the same manner as the "Increase Pressure" and "Decrease Pressure" buttons in the HMI.

5.8 Secondary muscle length as a function of main muscle length

To ensure a long lifetime of the pneumatic muscles, according to the documentation, the pressure should not go below 0.5 [bar] during operation. This is to avoid kinking of the tubes which can significantly reduce their working lifetime. In previous tests, only one muscle would be filled up corresponding to the input direction while the opposite muscle was exhausted. Due to the mounting of the muscles, their depressurized length is larger than the distance between the mounting points, thus causing the tubes to kink. The goal of this test is to determine a relation between the main muscle length and the secondary muscle length that avoids the secondary muscle being too long, resulting in a kink and at the same time making sure it is not too short such that it will interfere with the big concrete hose in the center.

5.8.1 Manual selection of positions

Appropriate combinations of pressure values for both muscles are collected by setting the main pressure to 1 [bar] and adjusting the secondary pressure value until an arbitrary distance between the secondary muscle and the center house is achieved. This combination [P1,P3] is written down and the process is repeated in steps of 0.5 [bar] up until a pressure value of 5 [bar].

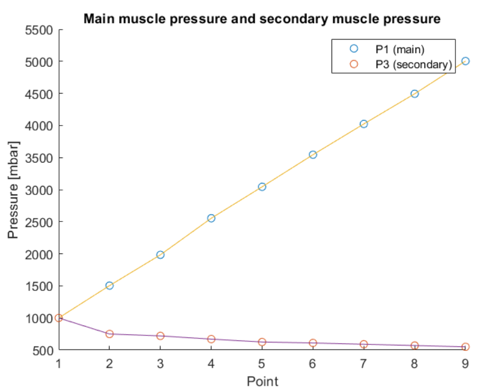


Figure 5.12: P1 and P3 at manually chosen points.

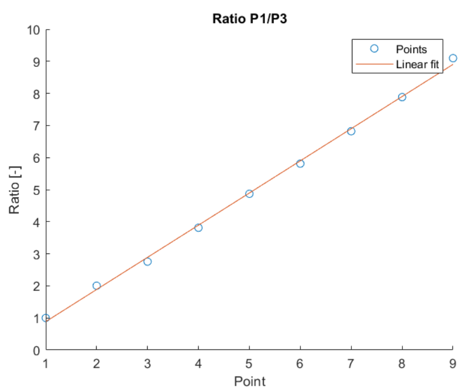


Figure 5.13: The ratio P1/P3 at manually chosen points with a linear fit.

As can be seen in Figure 5.13, the ratio P1/P3 follows a linear trend. The function that can be used for determining P3 given P1 is then found to be Equation 5.1.

$$P3 = \frac{500 \cdot P1}{P1 - 500} \tag{5.1}$$

After testing slight variations of Equation 5.1 the best physical behavior was noticed using Equation 5.2. One reason is that the muscle behaves differently when it is being used for some time. A warm muscle acts slightly slower than a cold muscle which would explain why a formula that results in a larger distance between the antagonistic muscle and the hose leads to better performance. A larger distance means the main muscle is allowed to shorten slightly quicker than the antagonistic muscle can lengthen. In practice, this can be confirmed by the distance between the antagonistic muscle and the hose decreasing while the main muscle shortens and once the main muscle reaches its desired length, the secondary slowly reaches equilibrium resulting in an increase in the hose distance, back to the original distance.

$$P3 = \frac{400 \cdot P1}{P1 - 450} \tag{5.2}$$

5.9 Analog joystick control

When pouring concrete, usually, a smooth, side-to-side swinging motion is required. This kind of motion can be achieved by using the analog outputs of the joystick on the remote controller. To allow the operator to control the position and orientation of the concrete tube during pouring, while being able to make fast adjustments, one mode of operation is to map the positions of the tube to the position of the joystick. Varying the degree to which the joystick is held in a certain direction directly correlates to the degree to which the concrete hose is positioned in that direction. The analog output of the remote controller will display a value between 0 and 28000 depending on how far the joystick is moved from the center. Where in the other tests the output pressure was increased or decreased by a certain increment when the joystick was pushed in a direction, in the analog control mode, the output pressure is determined using Equation 5.3.

$$P1 = \frac{J_x}{J_{xmax}} \cdot P_{max} \tag{5.3}$$

Where J_x is the analog output from the joystick, J_{max} the maximum analog output value and P_{max} the maximum allowable pressure in the air muscles, i.e. 6 [bar]. The remote controller analog outputs produce the same value for moving the joystick upwards compared to downwards and similarly, no distinction is made between left and right through the analog output. Therefore, four more digital outputs are used to determine if the joystick is moved upwards or downwards and left or right. In case this leads to a shortage of usable digital inputs for the PLC as there are only eight available, the same result can be achieved using only two by checking if the joystick is moved upwards through one digital input, if the output is FALSE, it means that the joystick was moved downwards. Using the same principle for left or right means that two joysticks can be represented using four analog inputs and four digital inputs in total, leaving four digital inputs and four analog inputs free for other purposes.

The joystick outputs values between 0 and 3000 when it is at the zero position so a deadzone of 5000 is used. This means that the PLC only actuates the proportional pressure valves when it receives an input larger than 5000. Since the joystick output fluctuates rapidly, this prevents the pressure valves and thus the air muscles from generating very quick, small movements when the joystick is at its center position.

Testing this approach showed that the mapping of the joystick position to the pressure value should not be linear. The difference in length of the muscle from 1 bar to 2 bar is much larger than the difference in length between 5 bar and 6 bar. In combination with the deadzone, a linear mapping leads to too low of a resolution at lower pressure levels causing the air muscles to contract too quickly with small movements of the joystick. To solve this problem, a quadratic mapping is used, yielding much better and smoother movements. Equation 5.3 is slightly modified to Equation 5.4.

$$P1 = \left(\frac{J_x}{J_{xmax}}\right)^2 \cdot P_{max} \tag{5.4}$$

The Codesys program written used to allow for analog control of two muscles in structured text (ST) is shown in Figure 5.14

```
ELSIF Start=TRUE AND Anamode=TRUE THEN
    IF J2Y>=5000 AND J2up=TRUE AND P3out<=pmin AND P1out<pmax THEN
        p1temp:=EXPT(INT_TO_REAL(J2Y)/28000,2)*INT_TO_REAL(pmax);
        P1out:=REAL_TO_UINT(p1temp);
    ELSIF J2Y>=5000 AND J2up=TRUE AND P3out>=pmin THEN
        P3out:= pmin;
    ELSIF J2Y>=5000 AND J2down=TRUE AND P1out<=pmin AND P3out<pmax THEN
        P3temp:=EXPT(INT_TO_REAL(J2Y)/28000,2)*INT_TO_REAL(pmax);
        P3out:= REAL_TO_UINT(P3temp);
    ELSIF J2Y>=5000 AND J2down=TRUE AND P1out>=pmin THEN
        P1out:=pmin;
    END_IF
END_IF
```

Figure 5.14: Codesys code in structured text (ST) used to achieve analog control.

5.9.1 Evaluation

When comparing both steering methods to each other, the analog control feels like it allows the operator to have better control of the hose. Digital control practically only has two options, move and do not move. While with analog modus, the operator gets the feeling that the hose really follows the position of the joystick. That being said, when the pressure increment size is large enough to make the airflow the limiting factor, which is usually the case when trying to create smooth movements, both steering modes feel practically identical. Ideally, the hose performs a smooth side-to-side motion perhaps only briefly stopping at the limits of its range. Since the airflow is the limiting factor both modes can achieve this by simply pressing the joystick fully in the desired direction then moving it to neutral for analog mode and moving it in the opposite direction for digital mode.

When looking at the future, assuming the flow rate will be increased, a more clear preference for one of the modes is expected to be found. When using digital mode in a scenario where the desired movement is slower than the maximum movement speed, the operator has to continuously move the joystick in a direction for a brief moment and then back, as the pressure increment is constant. This can be solved by adjusting the increment to match the desired speed but that will require calibration. Using analog modus, the smoothness of the motion can always be directly controlled by the operator. Thus the performance would depend more on how skillful the operator is.

5.10 Four muscle control

The next logical expansion is to implement the previous test on all four air muscles. The variable J2X is introduced in addition to J2Y, representing the movement in the x-direction. A copy of the innermost IF statement in Figure 5.14 is used for movement in the x-direction, where P1 is replaced by P2 and P3 is replaced by P4. Since the code is run every 20ms by the PLC, the diagonal movement of the joystick also works without any noticeable delay.

After confirming the expansion from two muscles to four muscles works as expected, the opposite muscle control as explained in section 5.8 is added to the program. Figure 5.15 shows part of the code that moves the prototype in the positive Y-direction which corresponds to a pressure increase of P1. The IF-statement checks if the joystick has moved out of the neutral position far enough, whether the movement is in the positive Y-direction, if the opposite muscle pressure is lower than an arbitrary value and if P1 is smaller than the maximum pressure. When all these conditions are true, a temporary variable for P1 is given the pressure value that corresponds to the position of the joystick. An IF-statement ensures P1 is larger than or equal to the minimum pressure. The opposite muscle pressure P3 is calculated based on P1 and an IF-statement checks if this is within the allowable range [pmin-pmax] before the temporary value is assigned to the final pressure variables.

```
IF J2Y>=Deadzone AND J2up=TRUE AND P3out<=5000 AND P1out<pmax THEN
    p1temp:=EXPT(INT_TO_REAL(J2Y)/28000,2)*INT_TO_REAL(pmax);
    IF p1temp<pmin THEN
        p1temp:=pmin;
    END_IF
    P1out:=REAL_TO_UINT(p1temp);
    P3temp:=UINT_TO_REAL(P1in)/((UINT_TO_REAL(P1in)-500)/450);
    IF P3temp<= pmax THEN
        P3out:=REAL_TO_UINT(P3temp);
    ELSE
        P3out:=pmin;
    END_IF
```

Figure 5.15: Part of the code (ST) that is used to control movement in one direction.

In addition, two buttons on the remote controller are used to be able to switch between modes of operation. Button one makes the robot move in so-called digital mode, where it moves with a constant pressure increment when the joystick is moved and button two makes it move in analog mode, where the robot moves to a position related to how far away the joystick is moved from the neutral position.

5.11 Improving steering behavior

What has become clear from the analog tests, is that the limiting factor in terms of movement speed of the hose is the outflow of air from the main air muscle. This is especially the case if the hose goes from 6 [bar] in one air muscle to the zero-point pressure, in most cases this is set to 800 [mbar]. The pressure drops rather quickly from 6 [bar] to 2 [bar], but the airflow significantly lags behind. What this means in practice is that the length of the muscle does not increase fast enough, or not as quickly as the pressure reaches the set point. This results in the air muscles crashing into the hose when an air muscle switches from being the main air muscle to the secondary air muscle. This behavior is observed each time that the hose switches between directions (positive x to negative x, positive y to negative y and vice versa).

The current steering modes do not prevent the operator from being able to move the joystick quickly and causing the muscles to crash into the hose. With the current setup, the only way to prevent this from happening is to add a set time delay. This is not optimal as any change to the setup would change the required delay. Using the pressure values also does not work since the pressure and the actual length of a muscle are not synchronized because the time it takes both these properties to reach their equilibrium differs significantly. The only way to determine the actual length of a muscle would be to add a flow sensor into the pneumatic circuit. This would allow for the design of a foolproof control that works regardless of the exact setup.

5.11.1 Determining the optimal working range

One way to increase the speed or smoothness of the motion of the hose through the change in direction is to maximize the outflow of air. At higher pressure values, the airflow out of a muscle is higher compared to the airflow at lower pressure. This means that increasing the minimum threshold of the air muscles, thus shifting the working range upwards would decrease the time it takes the muscles to reach their equilibrium state in terms of length. Practically, this can be achieved by mounting both ends of an air muscle closer to each other, as this requires the muscle to contract more before it starts moving the hose thus increasing the pressure threshold. An obvious disadvantage of this is that the physical range in terms of movement of the hose decreases because the force that a muscle can apply decreases with its length. To find the optimal solution, both physical range of motion and smoothness or speed have to be balanced.

5.11.2 Overview of challenges

While running all the different tests, certain phenomena are discovered. These phenomena can be translated into challenges that need to be solved when developing a program that controls the prototype. Changes in the prototype or setup might require different solutions for these challenges, which is why an overview of the currently relevant challenges is provided below.

- Opposite muscle control. To ensure a reasonable length of the secondary muscle, the relation between the primary and secondary muscle has to be determined. A constant secondary muscle length can cause the muscle to either kink or crash into the main hose. One way to determine this relation is to follow the steps as described in subsection 5.8.1. Manually adjust the pressure in both muscles to gather several appropriate positions, plot them and fit a curve through the points to derive the equation for P_x as a function of P_y.

- Avoiding collisions. Since the air flow rate out of the muscles significantly lags behind the pressure, it is possible for the muscle to collide with the hose when quickly switching directions. This can be prevented manually by the operator with some practice controlling the prototype and getting a feel for the controls. However, avoiding collisions from a control standpoint would naturally be better. One solution is to introduce a time delay for fast movements of the joystick but this would likely be different for all setups. The best way would, therefore, be to monitor the flow rate for each muscle and base the allowable movement on the actual length of the muscles. This solution would work for variations of the setup after the relation between the volume in a muscle, determined using the measured flow rate, is known.

- Balancing movement range and responsiveness. The flow rate out of the muscles is the main factor limiting the responsiveness or speed of the prototype. Finding an optimal working range in terms of pressure can lead to higher flow rates at the cost of limiting the physical movement range of the hose. Additionally, changes to the pneumatic circuit such as adding a quick exhaust valve close to the pneumatic muscle could improve the flow rate.

- Finding the optimal steering parameters for both modes. The increment size determines how quickly the pressure increases in a muscle when the joystick is moved. With the current setup, the increment size is chosen in such a way that the air supply determines how fast the hose moves. If at any point the maximum air supply rate becomes higher than the desirable movement speed, the increment size should be adjusted (lowered). For the analog steering mode, the mapping of the joystick position to the hose position is currently done with a quadratic relation. If the movement range changes, this relation might need to be adjusted.

6 Conclusion and Discussion

Looking back at the first research question: ”Can the operator guiding the hose during the pouring of concrete be replaced by an operator controlling the hose remotely?”, the results of the final test show promising results. Although the test did not involve actual concrete being poured, it showcases that an operator, with some training, would be able to control the hose remotely. Further effort is, however, required to smoothen the motion of the hose and to foolproof the controls by making sure it is not possible to move the hose too fast.

The second research question: ”Is a specific steering strategy optimal or preferred compared to another?” is difficult to answer when the differences are not very significant. It is likely best reevaluated after performing a wet test to determine what the effects of concrete in the hose are. For now, the operator can switch between steering modes with a simple press of a button on the remote controller. Looking ahead, however, it is likely that the analog mode will be the preferred mode of operation if the flow rate of the air can be increased.

The challenges that should be considered when further developing the controls for steering the hose using any type of setup include:

- Controlling the secondary muscle length based on the primary muscle length.
- Avoiding collisions between any of the muscles and the hose during operation.
- Finding a balance between movement range and speed.
- Determining the optimal steering parameters for both the digital and the analog steering modes.

Even though it was not used for any of the tests, there is another hose available with a larger diameter. This prototype features a slightly less sturdy attachment of the air muscles, using hose clamps instead of linking pieces. This hose is significantly stiffer and allows for variable attachment of the muscles. Combined with the fact that it allows a higher flow rate of concrete, means that it would likely perform better than the smaller hose. Since more weight is applied, the air is expected to flow out faster resulting in faster movements. This should be confirmed by running similar tests as was done for the smaller hose prototype.

The following solutions can be applied separately or a combination of multiple to increase the flow rate out of the PMA, thus increasing the lengthening speed, ultimately resulting in a faster allowable motion of the concrete pumping hose.

1. Decrease the distance between both ends of the PMA so that its operating range shifts upwards, for instance, 800-6000 [mbar] to 2000-6000 [mbar]
2. Increasing the weight of the hose will likely increase the force with which gravity pulls the muscle apart, thereby, increasing the flow rate.

3. Add a quick exhaust valve or a vacuum pump in the line to actively increase the flow rate out of the muscle. Adding a flow rate sensor in the circuit allows for determining the actual length of the muscles which can be used to avoid collisions by limiting the movement speed.

If, for any reason, these solutions cannot be applied, or the flow rate is still the limiting factor, an active delay should be implemented in the control of the robot that prevents too fast movements from happening. As the strengths and weaknesses are highlighted, a program for controlling the robot is developed that can form a solid base for further testing and improvement of the control.

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Appendix A

Title Appendix A

A.1 Setup

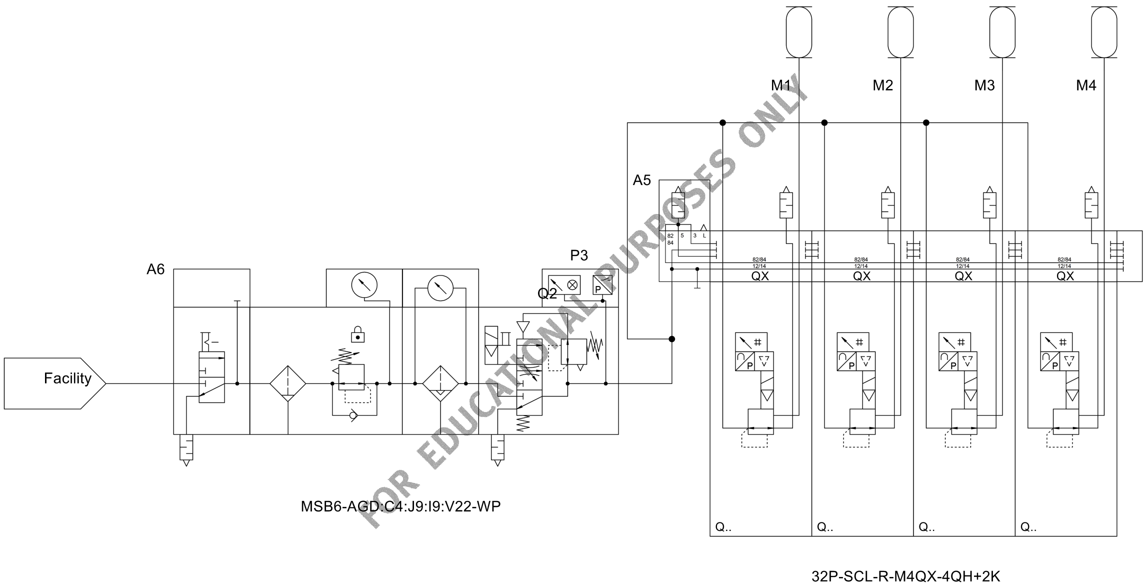

Figure A.1: Schematic overview of the pneumatic setup created in Festo's Fluiddraw.

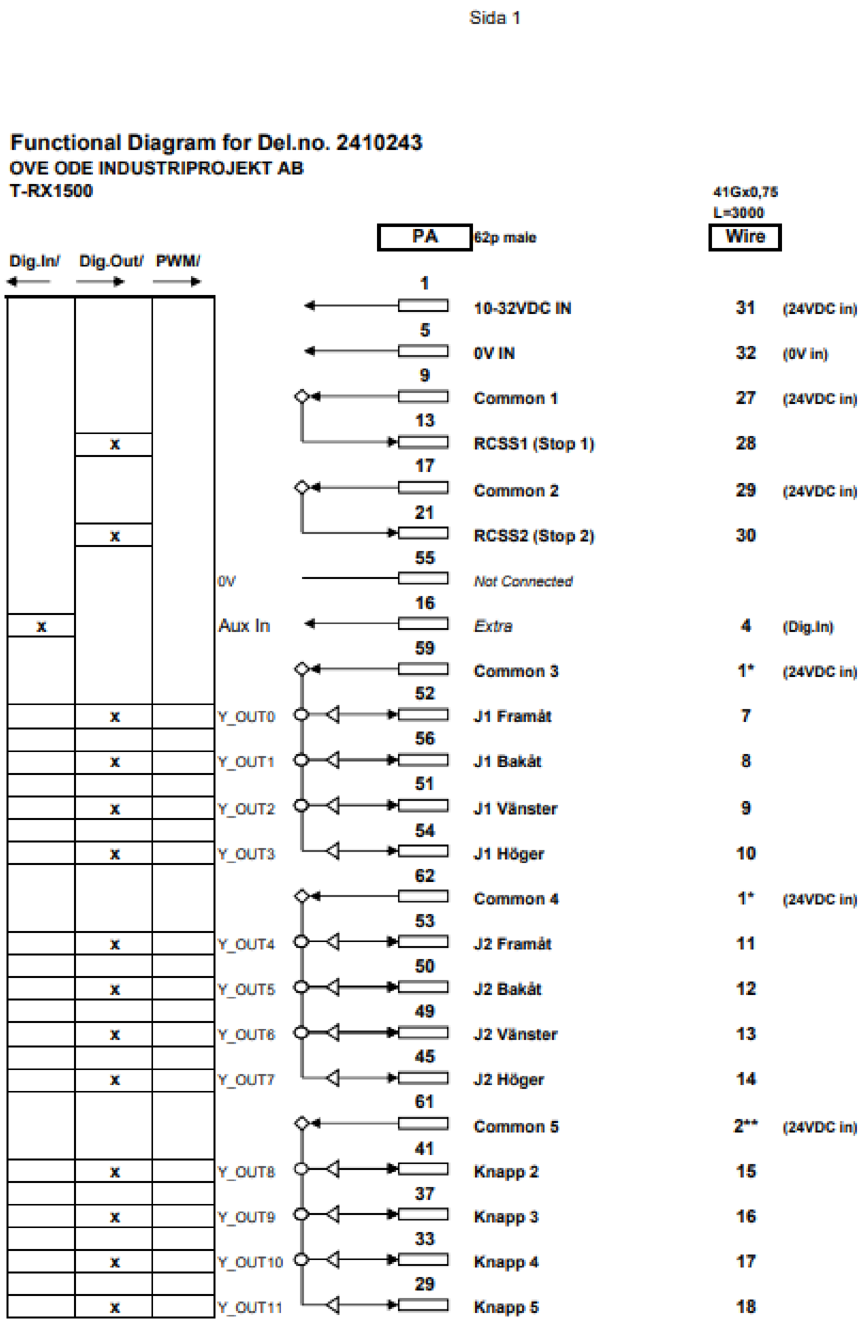

Figure A.2: Functional diagram for the remote controller, part one as provided by Åkerströms Björbo AB.

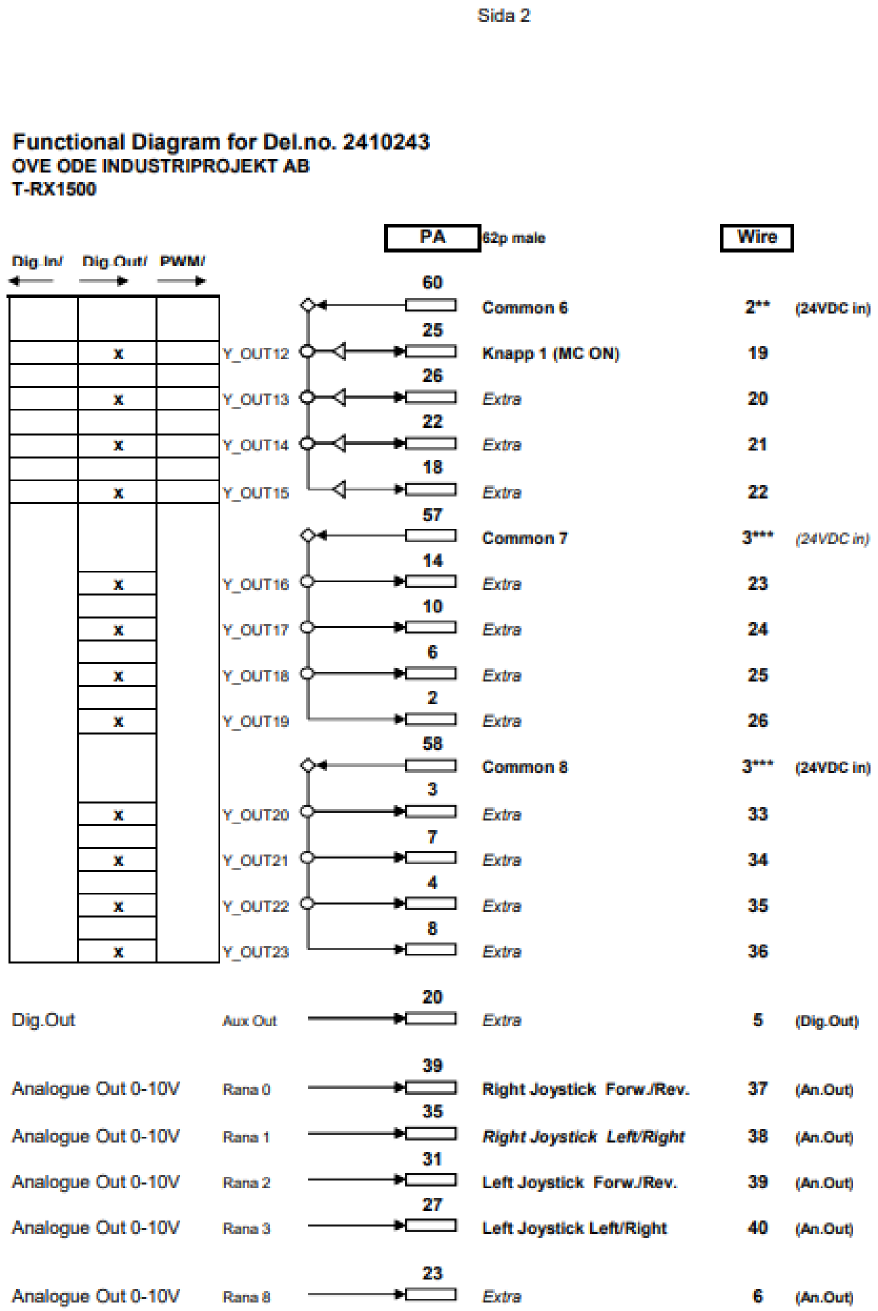

Figure A.3: Functional diagram for the remote controller, part two as provided by Åkerströms Björbo AB.

A.2 Code

The code for the most complete program can be found on my GitHub page (https://github.com/Ivo-Hoffmanns/MasterThesis/tree/main).