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Industrial Electrical Engineering and Automation

Automating the Opening and Closing Mechanism of a Functional Test Fixture

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Abstract

When producing printed circuit boards, end of line testing needs to be done to assure that as few faulty products as possible reach the customer. This can be done manually, but takes long time. By using a Functional Test fixture (FCT-fixture) it is possible to do the test faster and at a lower cost. A FCT-fixture is a fixture with a lid where the printed circuit board is placed. When the lid is closed needles are pressed on the printed circuit board's test points which, in turn, connects to a computer performing several tests.

Opening and closing the FCT-fixture automatically can save a lot of time and hence money in the end of line testing. Automating the opening and closing requires not only a solution for the opening and closing of the fixture, but also a solution for how to make the operation safe.

The aim of this thesis is to investigate the safety standards relevant for such an automation, coming up with a design for the opening/closing and safety, choosing one design, implementing it and evaluating the results.

The implemented solution automated all mechanisms except for closing. This was due to some miscalculations. One part of the solution was position measuring with an accelerometer. For the implemented solution the accelerometer was only used to determine the lid's end positions, but the possibility to measure the continuous angle of the lid was tested and implemented with the purpose of evaluation for future use and further implementation continuously requiring the lid's position. Implementing the safety solution was not done due to lack of time.

Acknowledgements

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Contents

Acronyms

I^2C Inter-Integrated Circuit. 17, 20, 42, 45

ABS Acrylonitrile Butadiene Styrene. 29, 33, 39

CAD Computer-Aided Design. 25, 26, 31, 33, 39, 41

CNC Computer Numerical Control. 27–29

DPDT Double Pole Double Throw. 36

DUT Device Under Test. 1–3, 17, 20, 22, 33, 36, 39

FCT-fixture Functional Test fixture. iii, xi, 1–4, 7, 10–15, 17, 20, 26, 27, 29, 31, 39–43

GND Ground. 36

I/O Input/Output. 36

IR Infra Red. xi, xiii, 14–17, 42, 52

MCU MicroController Unit. 1, 36

NUC Next Unit of Computing. 17, 31, 36

PCB Printed Circuit Board. 1, 35, 36, 41, 42

PID-controller Proportional Integral Derivative controller. 42

SPDT Single Pole Single Throw. 36

UART Universal Asynchronous Receiver-Transmitter. 4, 17, 20, 31

VDC Volt Direct Current. 17, 36

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1. Background

1.1 The functional test fixture and production line

To ensure that products sold by a manufacturer works properly, end of line testing of the products is very important. The manufacturer can save a lot of money if the faulty products are detected before reaching the customers.

Printed Circuit Boards (PCB) are a typical product that requires detailed and complex end of line testing. Are there any short circuits? Do all components have the right values (resistors, capacitors etc.)? Does the programming of the MicroController Unit (MCU) mounted to the PCB work properly? These are some questions that needs to be answered at the end of the production line. The slowest but easiest way of testing the finished PCB is to manually program and provide the PCB with factory settings and measure the voltage levels, resistance, digital signals etc. at different points on the PCB. This method is usually easily accessible and has a low start-up cost, but having an engineer do the end of line testing of PCBs is expensive and time consuming. For companies manufacturing higher quantities of PCBs that needs to be tested at a faster pace at a lower cost the FCT-fixture is a good choice. The start-up cost is much higher: the actual hardware is very expensive and every FCT-fixture needs to be customized according to the specific PCB that is going to be tested. Customizing the fixture requires a lot of engineering hours. When the FCT-fixture is in place, the testing of PCBs can be done much faster and more accurate. The testing time varies a lot but is typically around 5 minutes which is much faster than having an engineer doing it manually.

So how do an FCT-fixture actually work? There are several types: some are fully automated and does not need any operator and others need an operator to place the PCB on the fixture and close it. The principle however is the same for each type: on one side (usually the upper, in the lid) there are rods pressing on the PCB and on the opposite side there are needles pressing on chosen test points on the PCB. Figure 1.1 illustrates how a manually operated FCT-fixture works. When the PCB undergoes testing it is usually called Device Under Test (DUT). All test points are connected to a computer that performs several tests. The computer can output and input different voltage levels, communicate with the DUT via different protocols etc.

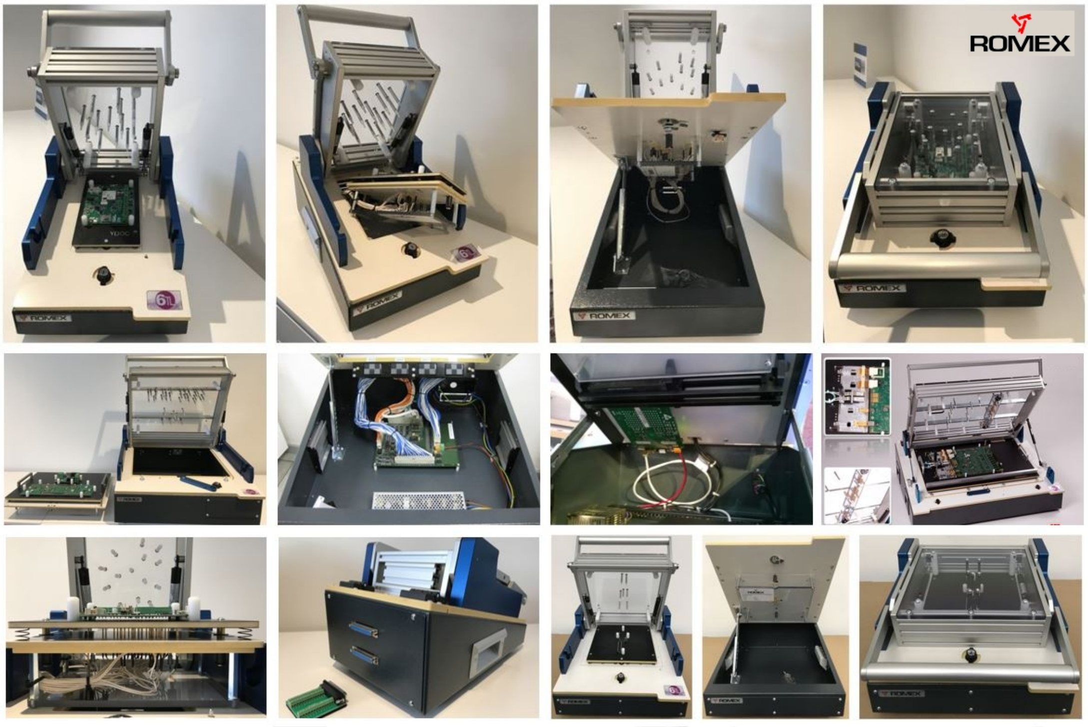


Figure 1.1: Several pictures of a FCT-fixture by MG modified by Romex. The needles are visible in the bottom left picture [6].

The fully automated version of the fixture usually feeds itself with DUTs on a conveyor. When the DUT is in place, the lid is automatically closed and the test is executed. This solution is very effective and does not require an operator which makes the continuous costs low. The problem with this solution is that it is usually big, bulky and very expensive.

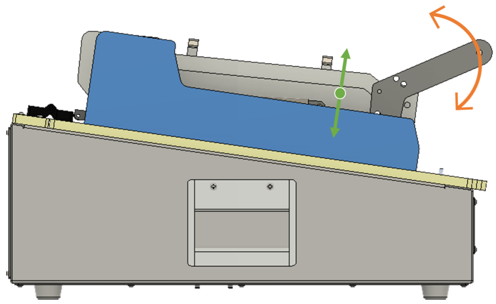
Then there is the manually operated FCT-fixture. It has a lower cost to produce and requires much less space. It however still requires an operator to run the fixture which costs money. The efficiency of a production line in a factory is very valuable. Every minute saved for each product adds up too much money.

The manually operated fixture consists of a shell (the box), an insert in the lid (containing the pins pressing on the DUT) and a cassette placed in the bottom of the box which contains the needles.

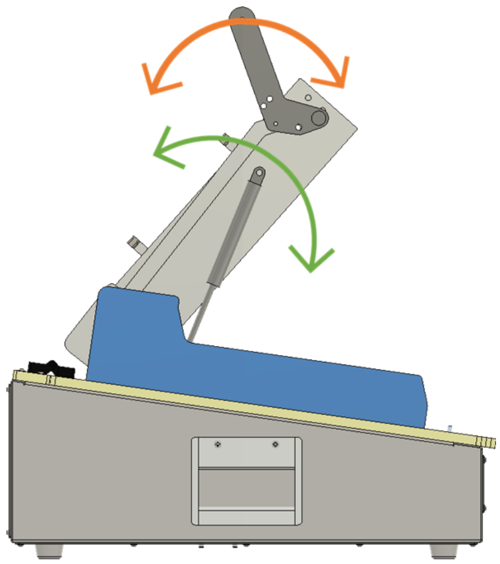
The aim of this thesis is to design a solution somewhere in between the fully automated and the manually operated fixture. Automating the opening and closing of the fixture can save a lot of time and make the work easier for the operators. Usually the operator loads, unloads, opens and closes several fixtures on the same line. Having an automatically opening and closing mechanism for the FCT-fixtures only leaves the loading to the operator. When all fixtures are loaded the operator can press one button closing all fixtures at the same time. When the tests are finished the lid is automatically opened and it is very easy for the operator to see which fixture is done.

1.2 Fixture movement and safety

The fixture used in this project is the MG 02-01 [3]. The design of how the lid moves for this model is similar to other models from other manufacturers (for example Ingun). The movement of the lid is not trivial. It can be divided into two motions. The first one is the actual opening and closing. This motion behaves as if the lid would be attached to hinges. The second one is the locking and unlocking of the lid. The last 20 mm, the lid will travel parallel to the rest of the FCT-fixture. The reason for this is that the needles must press perpendicular on the DUT. This means that the handle and lid travels at the same direction and speed when opening and closing the fixture, but different direction and speed when locking. Figure 1.2 illustrates the locking/unlocking and opening/closing of the FCT-fixture.



(a) This motion will be called locking or unlocking depending on the direction of the lid.



(b) This motion will be called opening or closing depending on the direction of the lid.

Figure 1.2: The orange arrows show the direction of travel of the handle and the green arrows show the direction of travel of the lid.

The closing and locking of the FCT-fixture create a risk for pinching. There is a big risk for the operator to pinch his or her fingers or hand if he or she is going to adjust something in the FCT-fixture and the lid starts closing. This is only one of the risks with automating this type of motion. Sound levels, unexpected start-ups etc. are also risks that needs to be considered. To do just that there are several EU-directives that must be followed. Following these directives also makes it possible for the product to be CE-marked. To make it easier to follow the directives there are so called harmonised ISO-standards that can be followed [1]. All harmonized standards regarding machine safety are listed in a file that can be found on the European website *Directive 2006/42/EC on Machinery - summary list as xls file* [9].

There are three types of standards: A, B and C standards. A-standards are the most general and C the most specific. If for example a B and C standard contradicts each other the C standard is to be followed. Most of the standards covered in this thesis are B-standards. The product that is going to be developed will be defined as a machine. The definition of a machine can be found in [1].

1.3 Scope and limitations

For this project only the machine directive will be investigated. Investigating the electrical directive is out of scope for the project. Following all harmonized standards connected to the machine directive suitable for one product is very hard and usually requires consultants that only deal with standards. For this reason, the safety standards will only be used as guidelines for this master thesis. There is no aim to fulfil all harmonized standards and make the product possible to CE-mark. It is however a goal to find what standards are the most important for this type of solution and summarize them. Knowing about these standards is important for future development of the solution.

Loading the fixture will not be a part of this project. Only the automatic opening and closing of the fixture will be designed for and implemented.

This project has some different areas and the aim was to investigate the following if there was more time at the end of the project.

- Fully implementing the safety solution to prevent pinching.
- Communicating with the computer performing the tests via Universal Asynchronous Receiver-Transmitter (UART).
- Fully controlling the position of the lid, not only opening, closing, locking or unlocking it.
- Measuring the position of the lid.

1.4 Outline

Chapter 2 Development, goes through all relevant standards and summarizes them. With the standards considered there are several design solutions for the opening and closing of the FCT-fixture and the safety of the whole solution. These are listed, evaluated and one of each solution is chosen.

Chapter 3 Implementation and results, contains the parts of the design that actually made it to prototyping and how the prototype was built. This does not only include the mechanical prototype but also explains what worked and what did not in the different parts of the solution.

Chapter 4 Analysis and discussion, analyses and discusses the results. The prototype is far from a fully working solution but is nevertheless valuable work. Discussing what did not work and the future improvements is one of the most important parts of the thesis and is found in this chapter.

Chapter 5 Conclusions, contains the conclusion of the project. Overall good and bad parts of the projects are mentioned and also some more general conclusions.

2. Development

The project started with investigating what standards apply and which parts of the standards that are relevant of the project. These standards will not be followed exactly, but will be a good guideline for the boundaries for the project. This chapter will start with explaining how harmonized standards and EU directives work followed by a list with all relevant standards and a short summary of them.

After all relevant standards were found, the design choices began. Various designs for opening/closing the FCT-fixture and the safety solution were listed, weighted and then evaluated. When a design was chosen, the circuit board design and code structure was chosen. Figure 2.17 shows a flowchart of the entire system and can be good to look at when reading trough this chapter.

2.1 Safety standards

To know what standards apply to this project the list of harmonized standards relevant to the machine directive [9] has been reviewed and all relevant standards has been listed, read through and summarized. This section lists those standards and summarizes them.

"Safety of machinery – General principles for design – Risk assessment and risk reduction (ISO 12100:2010)" [11]

[11] is a type C standard and treats general principles of machine construction. The document mentions other standards that are relevant to the project such as some relevant B-standards that should be taken into consideration.

Relevant for the project
Built in safety into the machine is much better than adding other safety solutions on top of the machine, but adding other safety solutions (like light curtains) is allowed. When adding external safety solutions it is very important that the solution is not easy to modify/remove and it should not make the operators job harder or slower; that can result in the safety solution being disabled by the operators in the factory. How safe the machine should be can vary depending on who is going to use it. The machine created in this project will only be used by operators in a factory. A requirement to educate the operators that are to use the machine can lower the safety requirements. It is important to note that educating the operators can not be used as replacement of removing the given risk element.
There is a list of the relevant sections from [11] in A.1 Standards.

“Safety of machinery – Emergency stop function – Principles for design (ISO 13850:2015)” [16]

[16] is a type B standard that describes how an emergency stop button should be implemented. The most important information from this standard is how the electronic emergency stop should be implemented from a circuit point of view. The description of where and how the emergency stop button should be placed and fastened is out of scope.

Relevant for the project
The purpose of an emergency stop is to prevent hazards derived from a persons behaviour or an unexpected risk-full event. It should always be accessible and it should not inflict other safety functions. When the emergency stop is activated it should remain activated until it is manually restored and when restored, it should not initiate starting of the machine. The emergency stop should not replace or impair any other safety functions. Electric and pneumatic equipment that perform the emergency stop function shall comply with relevant requirements from IEC 60204-1 and ISO 4414. It should have a red colour with a yellow background.

“Safety of machinery – Positioning of safeguards with respect to the approach speeds of parts of the human body (ISO 13855:2010)” [12]

[12] is a type B standard and describes how for example light curtains must be placed (distance, angle etc.) and how fast the machine should go into a fail-safe mode for the solution to be safe. This standard should be taken into consideration if we aim to use light curtains as safety feature.

Relevant for the project
Section 5 describes the stopping time and minimal distance that the safeguard should have and section 6.6 describes the distances for stretching over the safeguard. These numbers and calculations should be taken into consideration when designing the safety solution.

“Safety of machinery – Safety distances to prevent hazard zones being reached by upper and lower limbs (ISO 13857:2019)” [22]

[22] is a type B standard and states the safety distances needed when for example implementing safety cages for upper and lower limbs not to be hurt. This standard mainly describes the size of openings in a safeguard depending on what part of the body that is supposed to be protected from entering the machine.

“Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design (ISO 13849-1:2015)” [18] and “Safety of machinery – Safety-related parts of control systems – Part 2: Validation (ISO 13849-2:2012)” [13]

[18] and [13] are type B standards. [18] states requirements on code that is used for a safety feature. [13] describes how to test and validate the safety features implemented according to [18].

Relevant for the project
There are many strict requirements and these are too difficult to implement in this master thesis. The programming of the control system will not actively implement any of the requirements mentioned in this standard. The standards are however relevant for future development of the system.

“Safety of machinery – Prevention of unexpected start-up (ISO 14118:2017)” [20]

[20] is a type B standard that describes how unexpected start-ups can occur, what to do if it happens and how to prevent them from happening. There are some parts in the design where this should be taken into consideration for example the lid. An example of unexpected start-up can be that the mechanism holding the lid open fails and results in the lid closing.

Relevant for the project
The general idea that turning off the system or the system failing should not result in any dangerous situation, will be considered.

“Safety of machinery – Minimum gaps to avoid crushing of parts of the human body (ISO 13854:2017)” [21]

[21] is a type B standard that states minimal gaps that are required for protective safety solutions to not crush different parts of the body.

Relevant for the project
The minimum gap for fingers (2.5 cm) is the most relevant for this project is the safety solutions are implemented.

“Pneumatic fluid power – General rules and safety requirements for systems and their components (ISO 4414:2010)” [10]

[10] is a type B standard that treats the implementation of pneumatic systems.

Relevant for the project
Unexpected excess pressure can result in dangerous situations if not taken into consideration. It is important to keep the noise levels down since pressured air may

cause very high sound levels. It also states similar requirements as [20], for example that loss of power should not result in a dangerous situation.

"Safety of machinery - Electrical equipment of machines - Part 1: General requirements (IEC 60204-1:2016)" [17]

[17] applies to the electrical design used in combination with a machine.

Relevant for the project
This standard will not be taken into consideration since the scope of the project is to research the standards concerning machines. It is still a very important standard for future implementation of the solution.

2.2 Designs

There are two parts of the solution: opening/closing of the fixture and safety to prevent pinching. This section presents several design-solutions and their pros and cons.

2.2.1 Automating the opening, closing locking and unlocking mechanism

2.2.1.1 Servo motor on turning rotating axis

This design suggests connecting a servo at the rotating axis and controlling the opening and closing of the lid with the servo. At first glance, this solution can seem to be the most reasonable to apply. The benefits are that only one device is used to control the motion and it is fairly easy to replace. The problem on the other hand is that there must be a lot of modification done to the rig. Also, the axis, at which the lid turns when opening and closing is moving with the locking motion. That means that the solution must be designed so that the servo moves relative to the blue part (see figure 2.1). The size needed for the servo to be able to open and close the lid is also big. Even if the design looks good with only one servo controlling the whole motion, one more solution is needed for the locking and unlocking of the fixture. This will make the solution bulkier. Figure 2.1 roughly illustrates where the servo would be fitted to the FCT-fixture if implemented.

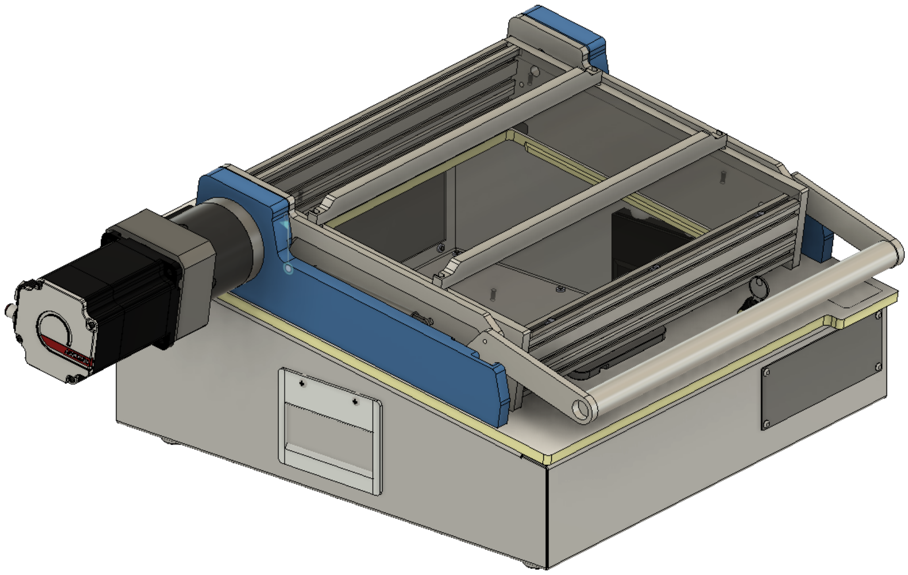


Figure 2.1: Illustration of how a servo could be placed to open and close the FCT-fixture.

2.2.1.2 Replacing the gas spring with pneumatic cylinder

This solution suggests replacing the already existing gas springs in the FCT-fixture with controllable pneumatic cylinders. One of the existing gas springs is visible in figure 1.2b right below the green arrows.

The benefits are that the cylinders will be well hidden and that there does not need to be much modification done to the fixture. The downside is that this solution, as the previous one, does not include a function for locking and unlocking the FCT-fixture. It is also very hard to find cylinders of this size that are strong.

2.2.1.3 Pneumatic cylinders outside the fixture, keeping the gas springs

This solution is similar to 2.2.1.2, but instead of replacing the existing gas springs with pneumatic cylinders, the cylinders are mounted to new mounts fastened outside the FCT-fixture. The existing gas springs are kept. There is also one extra cylinder controlling the locking and unlocking. Figure 2.2 shows the solution. This solution can be achieved with cylinders on both sides (a total of 4) or cylinders on only one side (a total of 2). I this project the cylinders will only be mounted to one side.

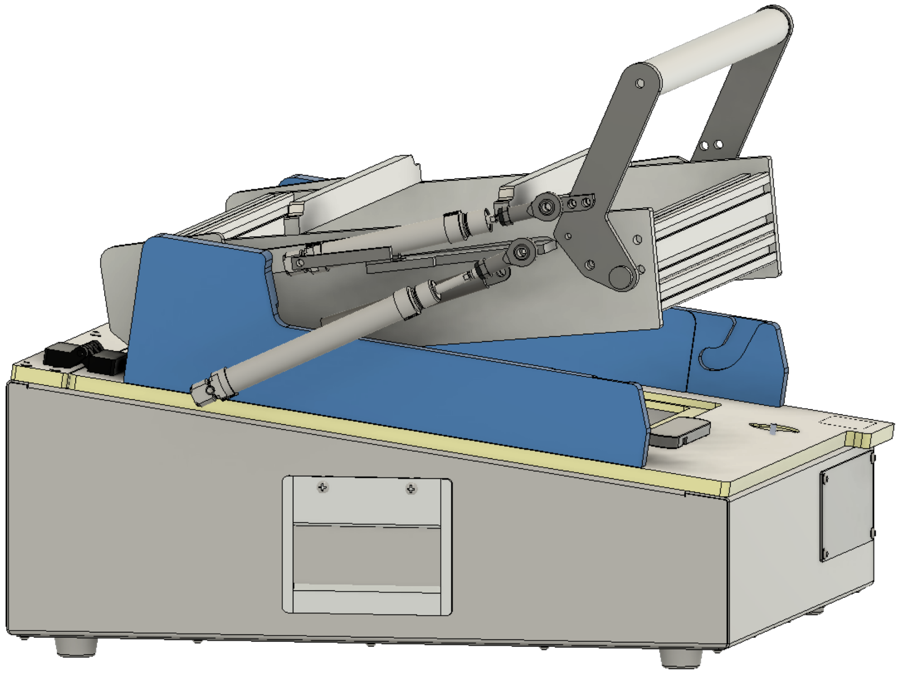


Figure 2.2: Illustration of how pneumatic cylinders could be fastened to automatically open and close the FCT-fixture.

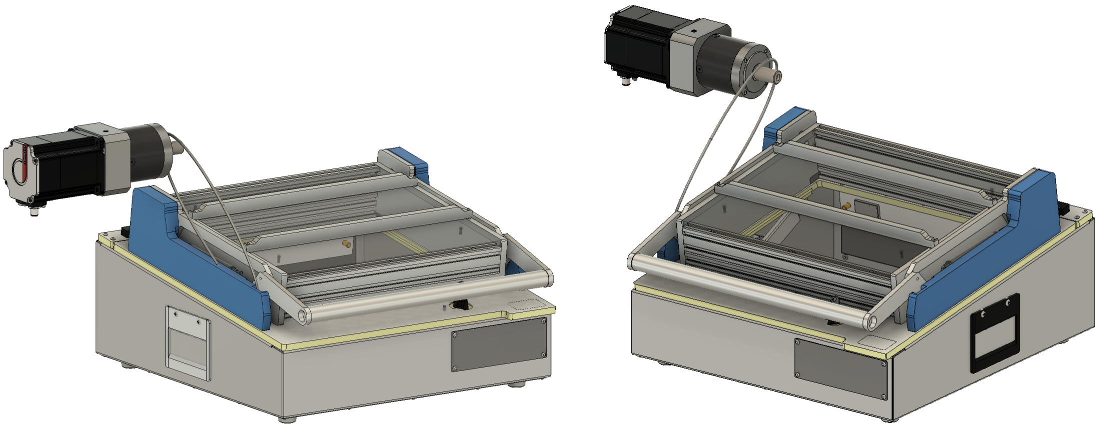
The downside is that the cylinders take up some space and can look bad. It is not possible to control the exact position of the lid, it either opens or closes. There are also some parts that must be manufactured and some modifications done to the FCT-fixture.

The benefits are that the cylinders are fairly compact when mounted to the lid. Even if there must be modifications done to the FCT-fixture, they are trivial and small. The cost of cylinders and manufacturing of the parts needed is small; the solution is low-cost. Additionally, the existing gas springs will function as an extra safety feature if the pneumatic cylinders were to fail.

2.2.1.4 Chain and Servo

This solution suggests a servo connected to a chain that pulls the lid for either opening or closing it. Figure 2.3 shows how the solution would look. The idea is that the chain is to be connected to a servo mounted a bit up from the FCT-fixture. Tracks are milled to allow the chain to slide inside the blue side plate. The chain is connected to the bearing on the handle (the biggest circle on the handle in figure 1.2b).

Since the bearing is moving in the same direction both for opening/unlocking and closing/locking this makes it possible for one servo to control all motions at once. The downside with this solution is that a lot of modification must be done. It is also not compact and nice-looking: there are a lot of moving parts mounted away from the FCT-fixture.



(a) (b)

Figure 2.3: A rough illustration of how a chain could be fastened to a servo to automatically open and close the FCT-fixture.

2.2.2 Safety to prevent pinching

Since the lid will automatically open and close there is a risk for pinching. To make the solution safe this hazard must be prevented; the system can either detect that somebody is present and stop the closing motion, or the possibility of entering the fixture with some part of the body while it operates can be removed. The relevant solutions available are either surrounding the hole FCT-fixture with a cage or detecting a body part with light curtains.

Classical light curtains have two parts: transmitter and receiver. The transmitter transmits light beams (lasers, infra-red light etc.) that the receiver receives. If a beam is broken (as shown in figure 2.4) the system has detected that something is where it should not be. This will result in a stopping of the current motion.

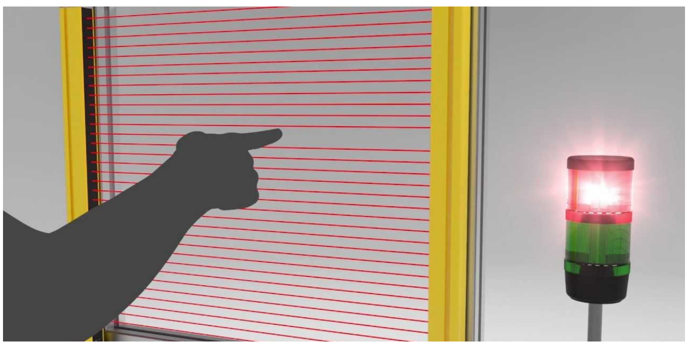


Figure 2.4: A classical light curtain [14].

2.2.2.1 Light curtain with transmitter and receiver in lid and bottom

This solution suggests putting transmitter and receiver in the lid and in the bottom of the FCT-fixture. The solution is very minimalistic, slim and nice-looking. There are some problems with it: it is very hard to implement. Since the angle between the lid and the fixture changes depending on the lids position, there must be some mechanical solution following the motion of the lid. This is hard to implement. There is also a lot of modifications needed to be done to the FCT-fixture for this solution to work.

2.2.2.2 Cage with hatch

Surrounding the FCT-fixture with a cage is a very safe solution: the risk of getting pinched is completely eliminated. The idea is to use a hatch that must be opened for the operator to remove or place a DUT in the FCT-fixture. The lid will only open, close, lock or unlock when the hatch is closed.

This is a very safe and low-cost solution. The problem is that it takes up a lot of space and requires the operator to open and close a hatch. Opening and closing the hatch almost eliminates the purpose of the automatic opening, closing, loading and unloading: why not just open/close the lid manually instead of opening/closing a hatch? A risk with this solution is that the operator might bypass the switch at the cage since it hinders and slows down the work.

2.2.2.3 Cage with light curtains

This solution is very similar to the previous, but instead of a hatch, light curtains are used to sense if something is present inside the cage. This removes the downside of having to open and close a hatch but adds complexity, cost and increases the risk of pinching.

2.2.2.4 Regular light curtains surrounding the whole fixture

This solution is similar to (2.2.2.2 Cage with hatch) but using four light curtains instead of a cage. The idea is to place one transmitter/receiver in each corner of the fixture. That will result in a light cage surrounding the fixture. The benefit is that the FCT-fixture becomes much easier to access from all angles. The downsides are that it is a much more expensive solution, the risk of pinching is higher than a mechanical cage and it is harder to manufacture.

2.2.2.5 Light curtains using Infra Red long-range proximity sensor

An Infra Red (IR) proximity sensor transmits and receives IR-signals. When something is in the way of the IR-beam, the beam gets reflected back into the sensor. This results in the sensor being able to detect objects. Some sensors can even detect the distance from the object to the sensor. See figure 2.5 for an illustrative picture of how the sensor works.

This solution suggests putting several IR long-range proximity sensors around the FCT-fixture pointing upwards. This will create a cage-like solution the same as 2.2.2.4. The benefits are that it is a lower cost solution and it can easily be put on the table at the same level as the fixture. There is no need to match the transmitter and receiver since they are in the same sensor which makes manufacturing the solution much easier.

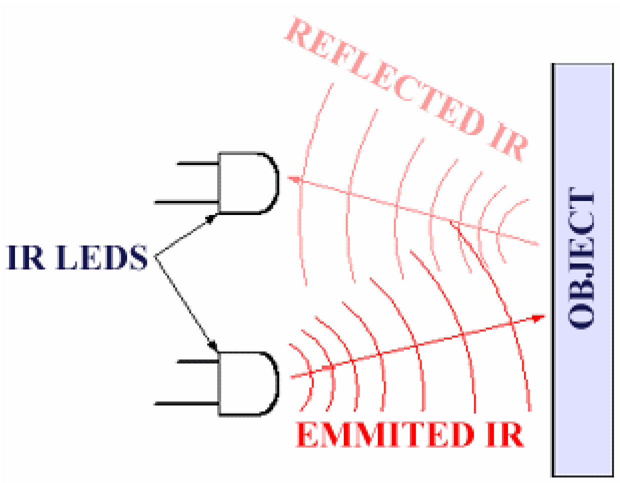


Figure 2.5: A simple illustration of how an IR proximity sensor works [7]. "OBJECT" is fingers, hands or arms in this case.

2.3 Choosing design

To choose one design two tables consisting of different design weights has been made. The result of the tables is taken into consideration when evaluating the different designs. These tables are shown bellow (table 2.1 and 2.2). The cost (serviceability, durability etc.) are different areas that are important for the solution. The "Value of cost" shows how much each cost area is worth ranging from 0 to 10). The total points are calculated by taking each value of cost and multiplying it with the value that the solution has at each cost and then sum up all of them.

Serviceability points at how easy the solution is to service. This cost is valued high since it can be very expensive to have FCT-fixtures standing still. It's also preferable that the operator can repair the mechanism rather than an engineer.
Durability points at how durable and robust the solution is. It's better to have a solution that does not break rather than a solution that is easy to repair but breaks down.
Manufacturability is an estimation of how easy and convenient the solution is to manufacture. This cost is valued high since the solution might be manufactured by an engineer instead of mass produced. For this master thesis it's also a big benefit to have an easy to manufacture solution.
Safety points at how safe the solution is to use. For the opening and closing mechanism the safety is not the most important part: the opening and closing will be a big risk factor. The idea is that the safety solution should take care of that risk. The safety is of course very important for the safety solution.
Cost is a very (but not the most) important part. The aim is of course that factories that buy the solution should save money with an increased productivity. A higher cost value is equivalent to a more affordable solution.
Noise is not very important for the solution. It is better to have a more silent solution but the design choice should not be made with this in mind. The safety solution will not have any noise, hence it is valued to 0.

Nice-looking solution is a bit vague. The though is that this cost should rate how "slender" the solution looks. For example, using one built in servo in the fixture that is not visible is a very nice-looking solution while having many different servos for different motions that take up much space is not very nice-looking. This cost is more important for the safety solution rather than the opening and closing solution. A safety solution that is not in the way for the operator can save a lot of time and be worth a lot.

Table 2.1: Design weight table for opening solutions.

Value of cost:	9	10	8	2	8	6	3	
Concept	**Serviceability**	**Durability**	**Manufacturability**	**Safety**	**Cost**	**Noise**	**Nice-looking solution**	**Total score**
2.2.1.1 Servo motor on turning rotating axis	8	8	2	9	4	9	9	**299**
2.2.1.2 Replacing the gas spring with pneumatic cylinder	8	8	0	9	10	4	10	**304**
2.2.1.3 Pneumatic cylinders outside the fixture, keeping the gas springs	8	8	8	8	10	2	4	**336**
2.2.1.4 Chain and Servo	5	5	5	5	4	9	9	**258**

Table 2.2: Design weight table for safety solutions.

Value of cost:	9	10	8	10	8	0	10	
Concept	**Serviceability**	**Durability**	**Manufacturability**	**Safety**	**Cost**	**Noise**	**Nice-looking solution**	**Total score**
2.2.2.1 Light curtain with transmitter and receiver in lid and bottom	6	8	6	5	5	0	8	**352**
2.2.2.2 Cage with hatch	9	10	8	10	10	0	1	**435**
2.2.2.5 Light curtains using Infra Red long-range proximity sensor	7	8	8	8	7	0	10	**443**
2.2.2.4 Regular light curtains surrounding the whole fixture	9	8	7	7	7	0	7	**413**
2.2.2.3 Cage with light curtains	8	9	9	9	9	0	6	**456**

2.2.1.3 gets the highest score of the opening and closing solution. 2.2.1.2 is almost the same solution but with a much nicer looking. This solution falls on the required size for the cylinders: there are no pneumatic cylinders small enough to fit inside the fixture. With this in mind 2.2.1.3 seems to be the best solution and is chosen.

Choosing between the safety solutions is a bit harder. One would say that 2.2.2.2 is much safer than all the other solutions, but this might not be true. One possibility is that the operator would disable the hatch mechanism if it hinders the operator to do the work fast and smooth as mentioned in standard “Safety of machinery – General principles for design – Risk assessment and risk reduction (ISO 12100:2010)” [11]. It is also important to think of the purpose of the design. To open and close a hatch would be almost the same amount of work as opening and closing the fixture. The other solutions that includes light curtains with both transmitter and receiver are easy to find already manufactured with all the safety standards implemented but are often very expensive and hard to mount nicely. All these factors make 2.2.2.5 the best design. These types of sensors have a low cost, are easy to use and only needs to be mounted on the bottom of the fixture.

2.4 The circuits

The electrical circuit needs to fulfil the following point:

- Transform the different voltage levels from 24 V to 5 V and then distribute them.
- Connect the Pyboard to relays for controlling the pneumatic valves.
- Connecting an emergency stop button.

- Connect the safety stopping feature (light curtains, hinge etc.) to the pyboard.
- Connecting all IR proximity sensors to get one output.

The pyboard is explained in section 2.5. The reason for using 24 V instead of 230 Volt Direct Current (VDC) is that 24 V is standard at Mikrodust.

The pneumatic circuit needs to:

- Limit the air pressure fed into the circuit from 8-10 Bar to 6-8 Bar.
- Distribute the air to all four different valves
- Connect the valves to the cylinders
- Limit the speed of the cylinders

It is standard where the FCT-fixtures are used to be provided with 8-10 Bar and the rest of the pneumatic system holds for 6-8 Bar.

Figure 2.6 shows the first version of the circuit. The input voltage (24 V) is fed into the voltage regulators to output 5 V (low voltage Vcc) and Vcomp. Vcc is then fed into the pyboard and the accelerometer. The accelerometer uses Inter-Integrated Circuit (I^2C) to communicate and send acceleration values in x, y, and z to the pyboard. The pyboard will connect to the master PC (in this case a Next Unit of Computing [2]) via UART. The NUC will for example tell the pyboard when the DUT-test is finished.

The pyboard outputs four signals to four different relays: two for each pneumatic cylinder. The first relays (connected to X1 and X3) sets if the second relays (connected to X2 and X4) will have 24 V or nothing as input. The second relays switch their input signal (24 V or nothing depending on the first relays) between the two valves. The valve that has high as input is the active valve. If the valve has nothing as input (X1 or X3 is off) then the active valve is the middle one. A truth table showing all four possible scenarios can be found in A.2

The circuit for the light curtain is placed in the top right. In this case four IR proximity sensors were used for illustration, but many more can be added. The output ranges from -0.3 V to Vcc + 0.3 V [8]. The operational amplifiers use Vcomp as a threshold for outputting 0 V or 5 V. If we for example want the sensors to react to a distance of 350 cm or further away, Vcomp should be 1.5 V. All the operational amplifiers connect to an OR-gate together with the emergency stop button. This part of the circuit will output 5 V if any of the sensors give an output higher than Vcomp.

To explain the pneumatic circuit let us consider only the left part of it, the right part works the same way. When the valve package is in the middle state both sides of the pneumatic cylinder will be directly connected to the flow control valves and the input pressure will be blocked. In this state it's possible to move the cylinder but the motion is dampened. When the valve package is in the rightmost state the input the right part of the cylinder will be connected to the input air and the left part will be connected to the damper. In this state the cylinder will push in the piston slowly (depending on how hard the damper is set). The left state is almost the same as the right, but the piston is pushed out instead. The air restrictors will act as sound dampeners as well as braking the air flow and the solution should be silent.

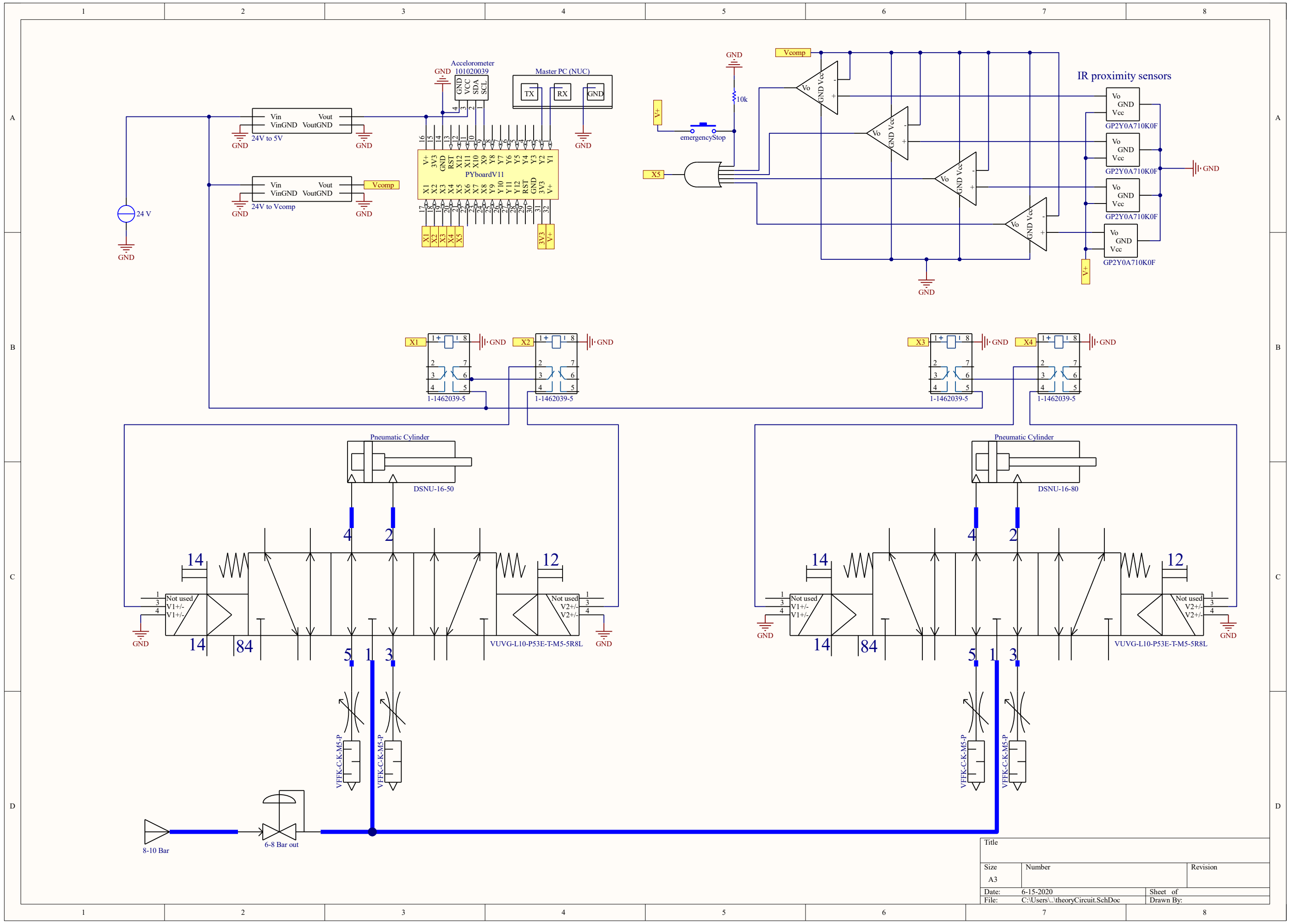


Figure 2.6: The first version of the circuit.

2.5 Software and the Pyboard

As earlier mentioned, the circuit will be controlled by a pyboard. Pyboard is a microcontroller board that runs MicroPython. MicroPython is a more efficient implantation of Python 3 with a subset of the standard python library. It is made to be able to run on microcontrollers [4].

The pyboard has several outputs and inputs that can be used in different applications [5]. Three types of outputs and inputs will be used:

- Digital outputs will be used to control the relays (controlling the pneumatic cylinders). Digital inputs will be used to receive the signal from the proximity sensors and to input analog buttons for debugging of the code.
- UART (Y1 and Y2) will be used to communicate with the Master PC (NUC).
- I^2C to receive the forces in x, y and z direction from the accelerometer. The combinations of these values are unique depending how open the lid is. This way the program can easily determine the lid's position.

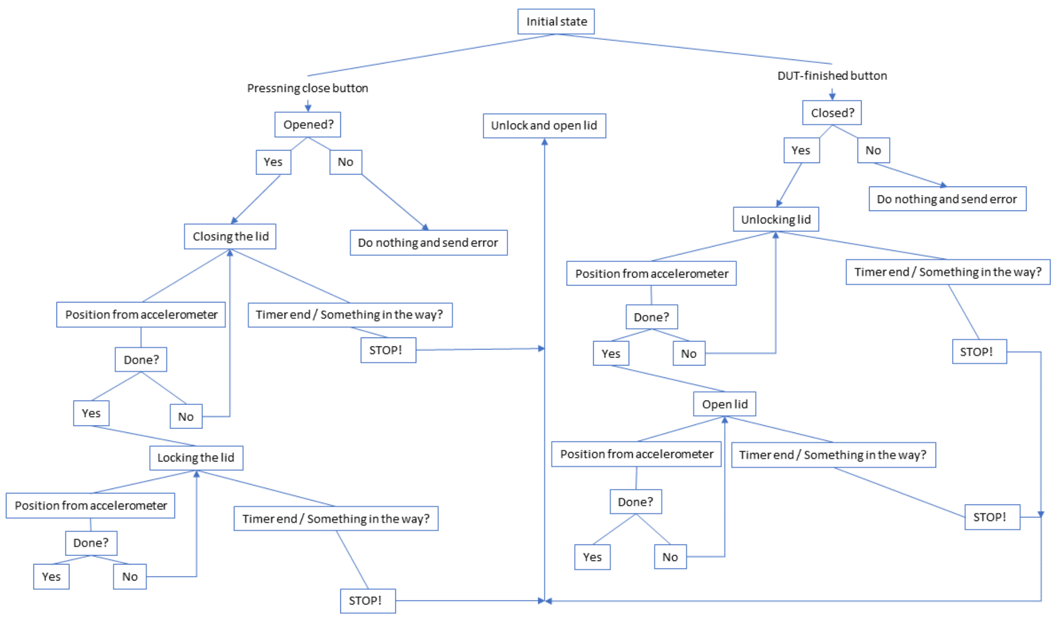


Figure 2.7: Flowchart over how the code should be generally implemented.

Figure 2.7 shows a simple overview of how the code should be implemented. The overall idea is that there are 3 input signals: closeFixture, dutFinished and lightCurtain. When the operator has placed the DUT in the FCT-fixture and want the lid to be automatically closed, **closeFixture** is pressed. When the DUT is finished the NUC will output a signal to the pyboard telling it to open the lid. This signal is **dutFinished**. The last signal is **lightCurtain** and acts as emergency stop. It is activated either by the emergency stop button or by breaking the light curtain. It is important for the program to stop immediately and open the lid when the lightCurtain signal is activated.

2.5.1 The code

The main code sets global variables, declares functions and then runs an infinite loop. The only event that can break the loop is the interrupt functions that are run when an input signal is activated. The interrupt functions do the following:

lightCurtain
The lightCurtain interrupt function will set the outputs to the relays in such a way that the cylinders unlock and open the lid. There is no feedback used in this state to check if the lid is open or stuck anywhere. When all the parameters are set the program will go into an infinite loop that does nothing. The purpose of this loop is to require a restart of the system for the system to be able to work properly again.

dutFinished
The dutFinished interrupt function sets the global variable dutFinished_interrupt to true.

closeFixture
The closeFixture interrupt function sets the global variable closeFixture_interrupt to true.

Following is a very simplified pseudo version of the main code:

```
def pinDebounce(pin):
    # This function samples 32 values from the button input
    # and returns True when the values are the same


def lightCurtain_Callback(pin):
    if pinDebounce(pin):
        # The outputs connected to the relays are
        # set so that the lid is unlocked and opened.
        while True:
            # This is the infinite loop that runs until
            # restart

def dutFinished_Callback(pin):
    if pinDebounce(pin):
        dutFinished_x6_interrupt = True

def closeLid_Callback(pin):
    if pinDebounce(pin):
        closeFixture_x7_interrupt = True

while True:
    if dutFinished_interrupt == True:
        # Unlocks and opens the lid of the FCT fixture
    elif closeFixture_interrupt == True:
        # Closes and locks the lid of the FCT fixture
```

The pinDebounce-function is important since there is some ripple when first pressing an analog button. This function filters out that ripple.

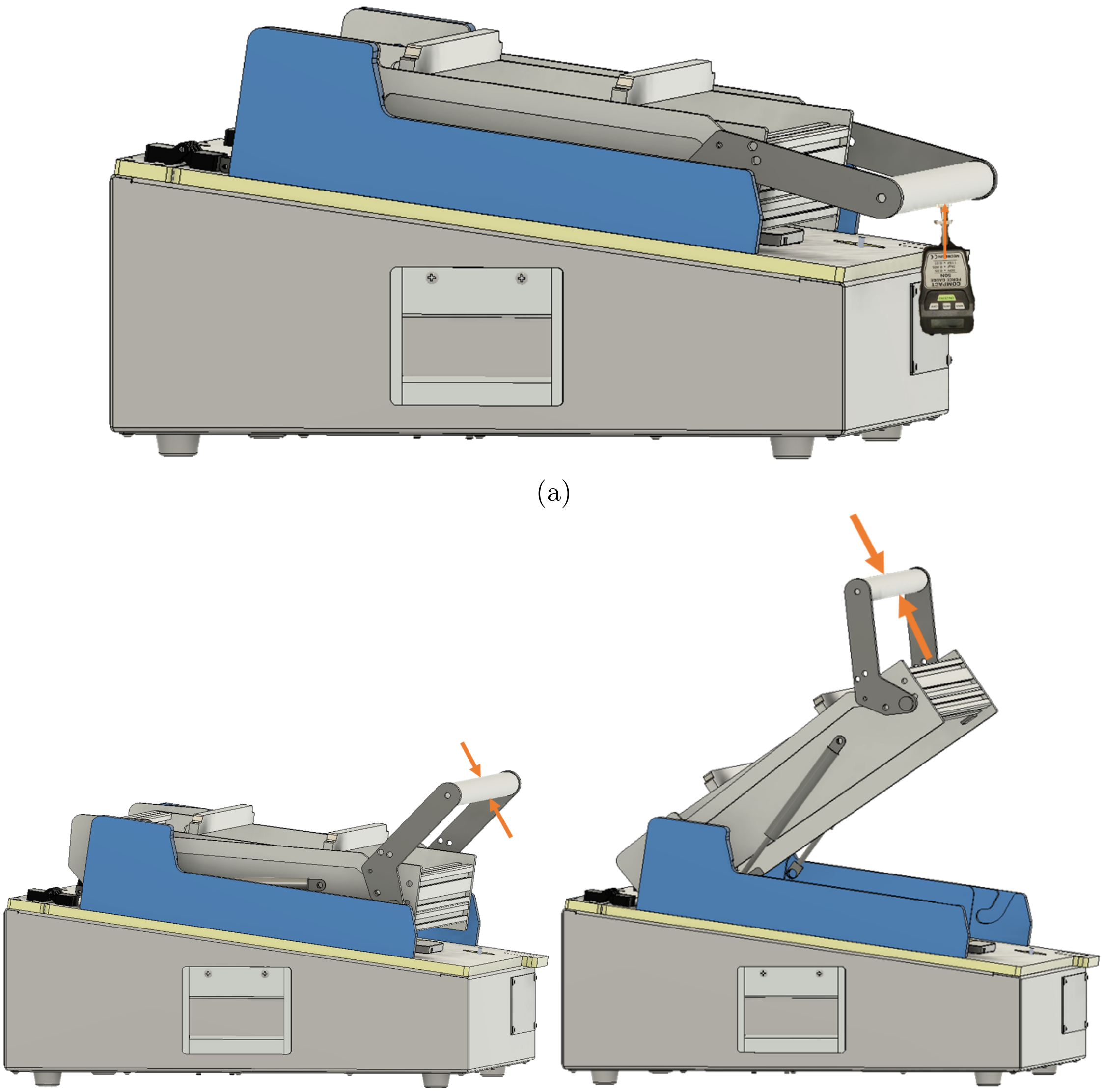
A callback (interrupt) -function should be entered and exited as quickly as possible. The main reason for this is that no other interrupt function can interrupt an already ongoing interrupt function. That is the main reason that the functions are defined inside the main loop instead of directly in the callback-functions. The exception is lightCurtain_Callback: this function must be possible to enter at all time and should not be possible to interrupt. The only state where the lightCurtain_Callback will not be entered directly is if the code is executing one of the other callback-functions. On the other hand, these callback-functions will be exited very quickly since they only change the value of one variable and because of this it will not matter from a safety point of view.

The lid is closed in the following way: the accelerometer is checked to see if the lid is opened. If it is opened the output values to the relays are set in such a way that the biggest cylinder retracts and the lid closes. These values are kept until the accelerometer outputs values are indicating that the lid is closed but not locked or a timer (for example set to 10 seconds) has ended. If the lid gets to the position closed but not locked the same algorithm is executed from closed not locked to close and locked. The algorithm for opening the fixture is the same with the same timers. If the timers end the program will go into emergency stop mode.

2.6 Force measurement

The forces required for opening, closing, locking and unlocking the fixture need to be known to design the actuators properly. To get a rough estimate of how large the required forces are these forces have been measured.

The forces were measured with a force gauge (Mecmesin 860-021, CFG+ 50 N), always by pushing on the handle with as little force as possible (see figure 2.8). A cassette, lid and DUT were placed in the fixture to get as reliable force measurements as possible. It is not possible to keep the same angle throughout the push, changing the angle will result in a higher force than needed. That is not a problem since the smallest force is sought.



(a)

(b)

(c)

Figure 2.8: The orange arrows show how the force gauge was pushed to measure the forces. Figure 2.8a also shows a picture of the force gauge.

Figure 2.9 illustrates the angles and forces used to estimate the force required from the cylinders.

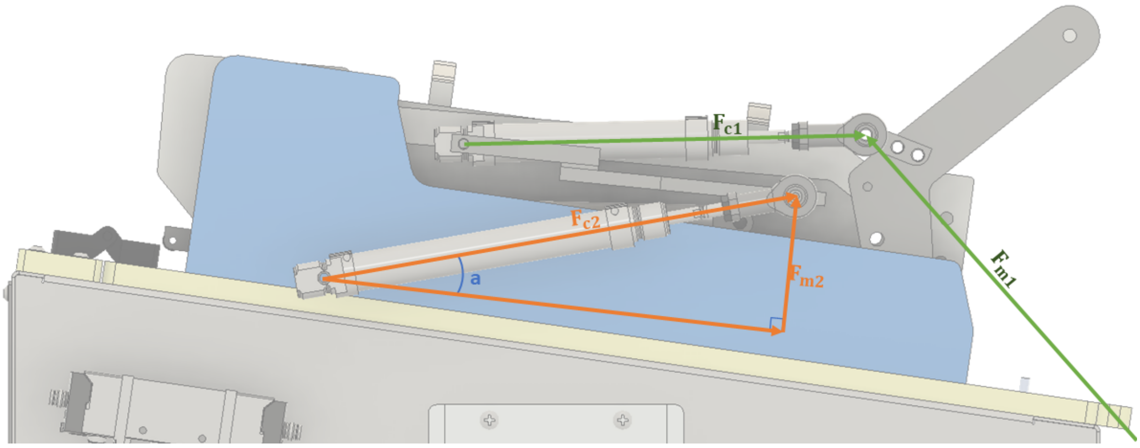
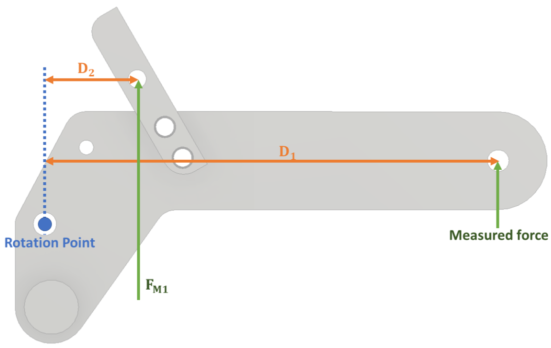


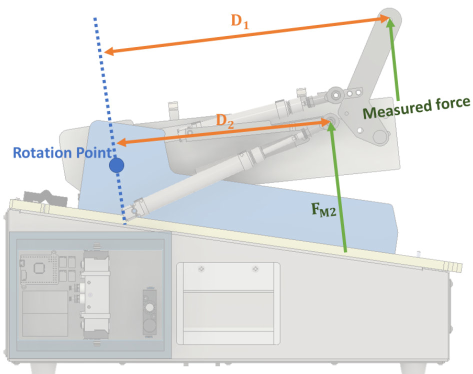
Figure 2.9: Illustration and notation for force calculations. F_{m1} is perpendicular to the handle.

The calculation is divided into two steps. The first is to calculate the forces F_{m1} and F_{m2} from the measure force and the second is to calculate the forces F_{c1} and F_{c2}.

F_{m1} and F_{m2} are calculated in a similar way: the force is measured on the handle and F_{m1} and F_{m2} are just scaled around the rotating point. The distances D_1 is the distance where the original force is measured and D_2 is the distance to where the wanted force is. These distances can be found in figure 2.10.
For F_{m1}, $D_1 = 125$ mm and $D_2 = 12$ mm. This means that $F_{m1} = \frac{125}{12} \cdot$ the measured force $= 10.5 \cdot$ the measured force.
For F_{m2}, $D_1 = 400$ mm and $D_2 = 250$ mm. This means that $F_{m2} = \frac{400}{250} \cdot$ the measured force $= 1.6 \cdot$ the measured force.



(a) $D_1 = 125$ mm and $D_2 = 12$ mm.



(b) $D_1 = 400$ mm and $D_2 = 250$ mm.

Figure 2.10: The forces measured

The measured forces scaled to F_{m1} and F_{m2} are not displayed. If wished for, they can easily be calculated by taking F_{m1} or F_{m2} multiplied with $\frac{D_2}{D_1}$. F_{m1} and F_{m2} are found in table 2.3.

The next step is to calculate what force the cylinder needs to push or pull with. F_{m1} is always pushing roughly at the tangent line of the handles direction (see the orange arrows in figure 1.2). The force F_{c1} is also pushing roughly at the tangent line of the handles direction, hence it is assumed that $F_{c1} = F_{m1}$. To calculate F_{m2} simple geometry is used. Equation (2.1) shows the expressions for F_{c1} and F_{c2}.

$$\begin{aligned} F_{c1} &= F_{m1} \\ F_{c2} &= \frac{F_{m2}}{\sin a} \end{aligned} \tag{2.1}$$

There are two extreme cases that can happen and must be taken into consideration: Both gas springs working on the fixture and neither of them working. Table 2.3 shows the different forces for the different scenarios.

Table 2.3: Calculated forces for the cylinders.

Scenario	Stage	Angle 1 [°]	Force measured [N]	Force wanted [N]	Angle 1 [°]	Force measured [N]	Force wanted [N]	Lid direction
2 gas springs	Locking/	-	44.3	44.3	-	F_{M1}	F_{c1}	Unlocking
	Unlocking	-	35.8	35.8	-	$-F_{M1}$	F_{c1}	Locking
	Closing/	27.7	15.3	32.9	a	F_{M2}	F_{c2}	Opening
	Opening	27.7	-41.9	-90.2	a	F_{M2}	F_{c2}	Closing
No gas springs	Locking/	-	44.3	44.3	-	F_{M1}	F_{c1}	Unlocking
	Unlocking	-	35.8	35.8	-	$-F_{M1}$	F_{c1}	Locking
	Closing/	27.7	28.4	61.1	a	F_{M2}	F_{c2}	Opening
	Opening	27.7	10.0	21.5	a	F_{M2}	F_{c2}	Closing

Mounting the cylinders according to the chosen design (2.2.1.3 Pneumatic cylinders outside the fixture, keeping the gas springs) the forces required from each cylinder are:
Upper cylinder taking care of the locking and unlocking: retract force = 44 N and advancing force = 44 N.
Lower cylinder taking care of the opening and closing of the lid: retract force = 91 N and advancing force = 62 N.

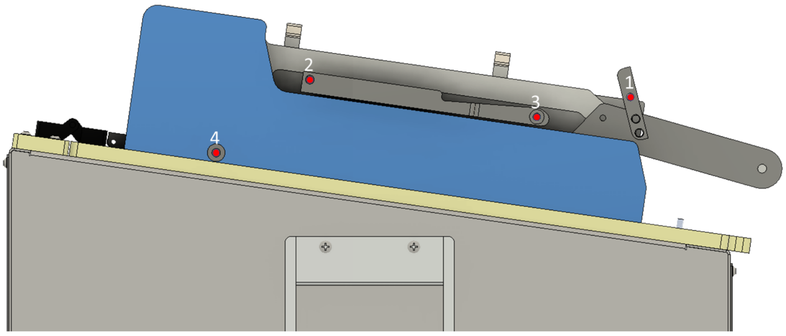
In table 2.3 it is assumed that the angle a is the same for when the lid is opened and closed. This was shown to not be true. The Angle for the close lid is, as shown in table 2.3, 27.7° but for the open lid the angle is actually 12.1°. This results in a maximum force of 200.1 N. It is important to point out that the calculations and measured angles in table 2.3 is the one used to design the cylinders. The only error is the b for when the lid is fully opened.

2.7 Mechanical design and cylinder length calculations

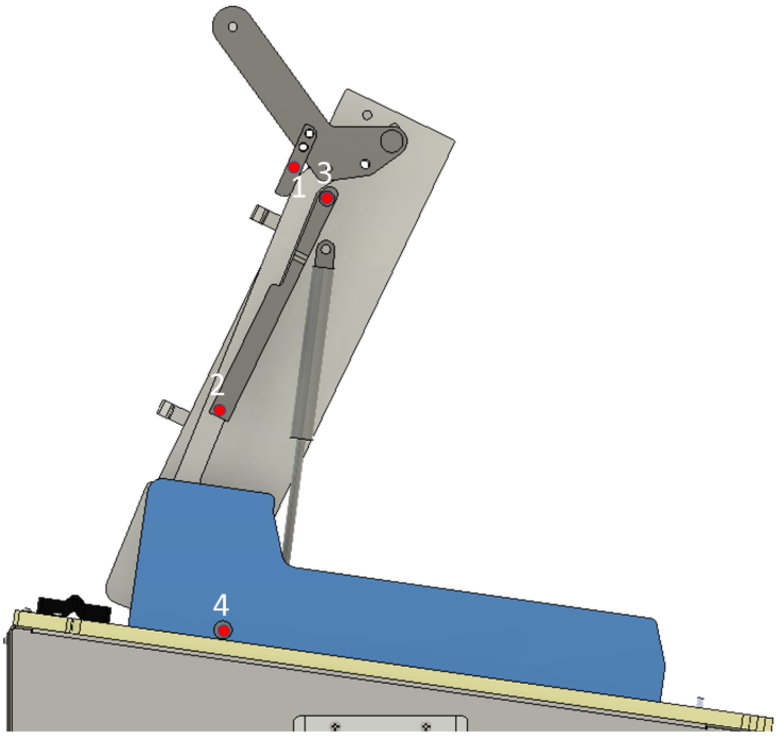
The solution should be slender. This means that the margins are very small. Using the Computer-Aided Design (CAD) program Fusion 360 where a CAD-model of the fixture with moving part is available, all measurements needed to determine the specifications of the cylinders and placement of them could be made.

2.7.1 Lengths

Figure 2.11 illustrates the length that needed to be calculated in the CAD-model. If a straight line is drawn from point 1 to point 2 and another line from point 3 to point 4 in each picture we have four lines. Let us call them 12closed, 12opened, 34closed and 34opened.



(a) Fully closed FCT-fixture.



(b) Fully opened FCT-fixture.

Figure 2.11: The red dots illustrate the points that are used for measurement when the fixture is closed and opened.

The results from measuring the lengths in the CAD program are:
12closed = 220 mm
12opened = 170 mm

34closed = 212 mm
34opened = 287 mm
Lets call the differences between the length 12diff and 34diff:
12diff = 52 mm
34diff = 74 mm
These lengths are important when choosing the two cylinder lengths later in the report.

2.7.2 Cylinder mounting design

The cylinders need to be mounted to the FCT-fixture at two connection points: the end of the cylinder and the end of the piston. The first idea was to connect the cylinders connection points to a single spacer as shown in figure 2.12.

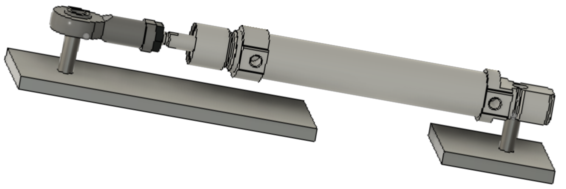
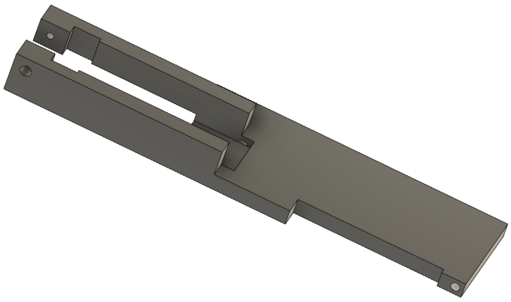


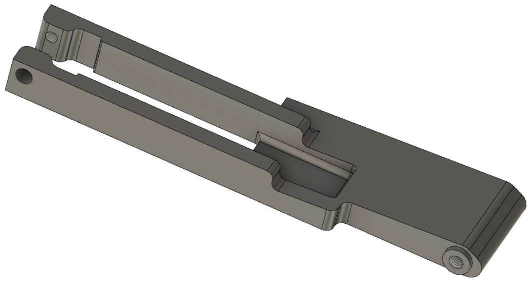
Figure 2.12: Illustration of how two spacers would be connected to the pneumatic cylinder. The two rectangular blocks that the cylinder is connected to represent two moving parts of the fixture.

This design was quickly dismissed since there will be a big risk for the spacers to break due to single shear and fatigue.

The next idea was to increase the area where the cylinder mounting is connected to the FCT-fixture and add some more holes for the screws. This resulted in a plate mounted to the lid of the fixture as shown in figure 2.13. This part uses a double shear fastening point for the back of the upper cylinder and mounts much more rigidly to the FCT-fixture. The first version was designed to be able to manufacture in a Computer Numerical Control (CNC) -machine (figure 2.13a). This is why there are no gradients or other complex shapes in the design. After deciding to manufacture the part by 3D-printing it there was a slight redesign of it (figure 2.13b). The part could be made thicker where it mounts to the fixture to have more material around the mounting holes. Figure 2.16 shows the 3D-printed version mounted to the fixture.



(a) Side plate designed for CNC manufacturing.



(b) Side plate designed for 3D-printing.

Figure 2.13

To fasten the lower part of the lower cylinder a simple spacer was designed. As mentioned before this spacer will be exposed to large bending forces due to single shear, but it is very short so there should be no problem using that design if it is manufactured in steel. Figure 2.14 shows this spacer and figure 2.16 how it is mounted to fixture.

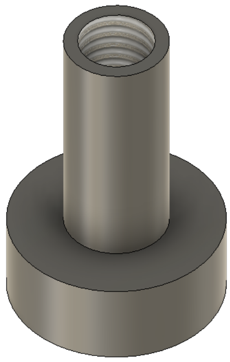


Figure 2.14: The spacer used to fasten the lower part of the lower cylinder to the fixture.

The last point that needs to be mounted to the fixture is the upper part of the upper cylinder. This part should be fastened to the handle to move it. Figure 2.15 shows this part and figure 2.16 shows how it is mounted to the handle. Two M6-bolts are needed to fasten this part to the fixture and one M6 bolt to fasten the cylinder to the part. Using two bolts the structure is rigid and does not allow for the part to turn.

Figure 2.15: The mounting part that is fastened to the handle.

An accelerometer will also be fastened to this part measure the position of the lid.

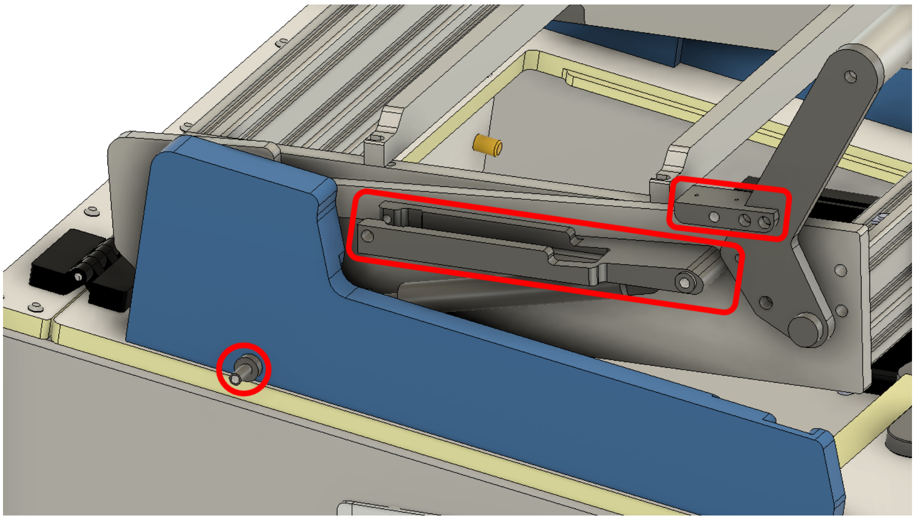


Figure 2.16: All cylinder fastening parts mounted to the FCT-fixture. The parts are circled in red.

As earlier mentioned, the idea was to manufacture all parts in a CNC-machine. It was later decided that the parts should be 3D-printed in Acrylonitrile Butadiene Styrene (ABS)-plastic. 3D-printed ABS-parts usually have a lower strength than parts made of metal, but was thought to be sufficient for testing.

2.8 Overview of the entire system

Figure 2.17 shows an overview of the entire system. The idea is that everything should be nicely packaged into a box that only requires 6-10 bar and 24 V input. For this thesis the box will be located outside the FCT-fixture, but later it could be built into the FCT-fixture making way for a much nicer looking and sleek design.

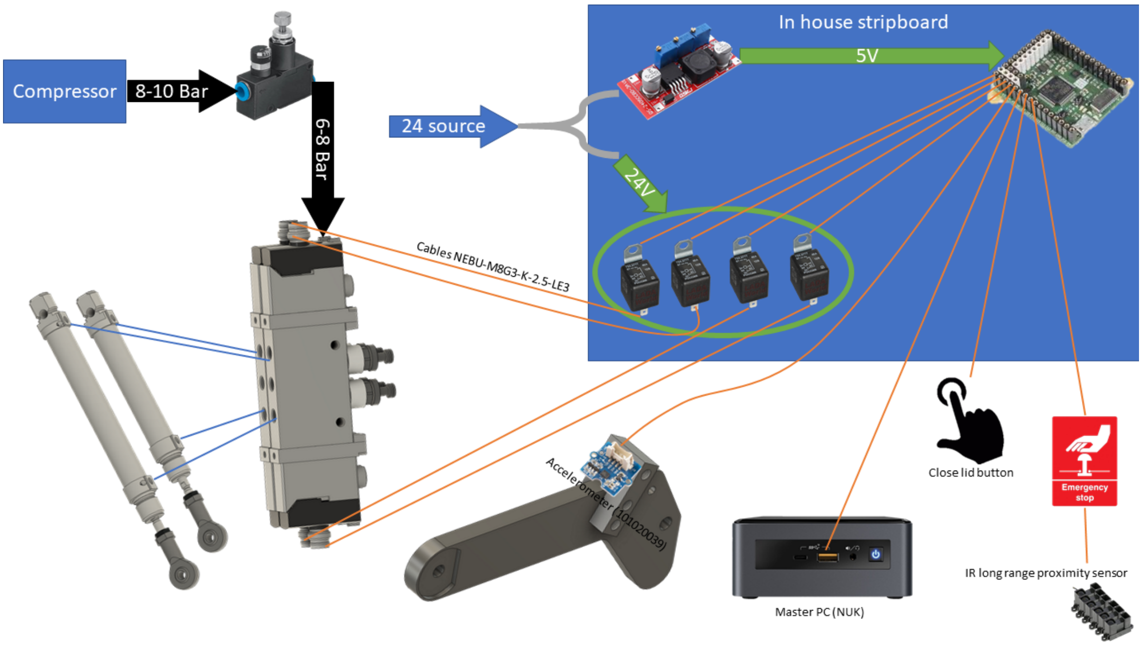


Figure 2.17: A flowchart over the entire system.

3. Implementation and results

The main task after design and standard definition of this project was to implement the design and build and mount the solution on the FCT-fixture. One part of implementing the design is to design all components properly. For the mechanical part this means designing the pneumatic cylinders and valves. To do that some calculations on the forces required to open, close, lock and unlock the fixture are presented in the previous chapter. For the electrical part this means that components with the right voltage and current specifications needs to be found.

3.1 Circuit implementation

All components mentioned below can be found in the bill of materials in table A.3. The first choice made was what valves should be used. Choosing components for the pneumatic system was very straight forward after that. Many components such as: hose, connections, pressure regulator etc. were already available in the workshop and were chosen simply because they worked well enough. Choosing the pneumatic cylinders was done by calculating the maximum and minimum lengths required in the CAD-model and using the forces calculated from the measurements (see chapter 2).

The electrical specifications of the valves and the pyboard is what is needed to design the relays that are going to be used. Some changes were done to the circuit by simplifying it due to lack of time in the project:

- The light curtains were replaced with a button
- Since the light curtains were removed the voltage regulator for the comparators could also be removed.
- The NUC was also replaced with a button. The communication via UART was not implemented.
- Pressure regulators were connected in series with the input air pressure

The first testing and development of the program was done with the circuit connected on an ordinary breadboard. The pneumatic system was not connected or implemented but testing of the accelerometer could be done by opening and closing the lid by hand. After writing the first version of the program the mechanical system could be fully implemented and tested together with the program.

The modified circuit is shown in figure 3.1.

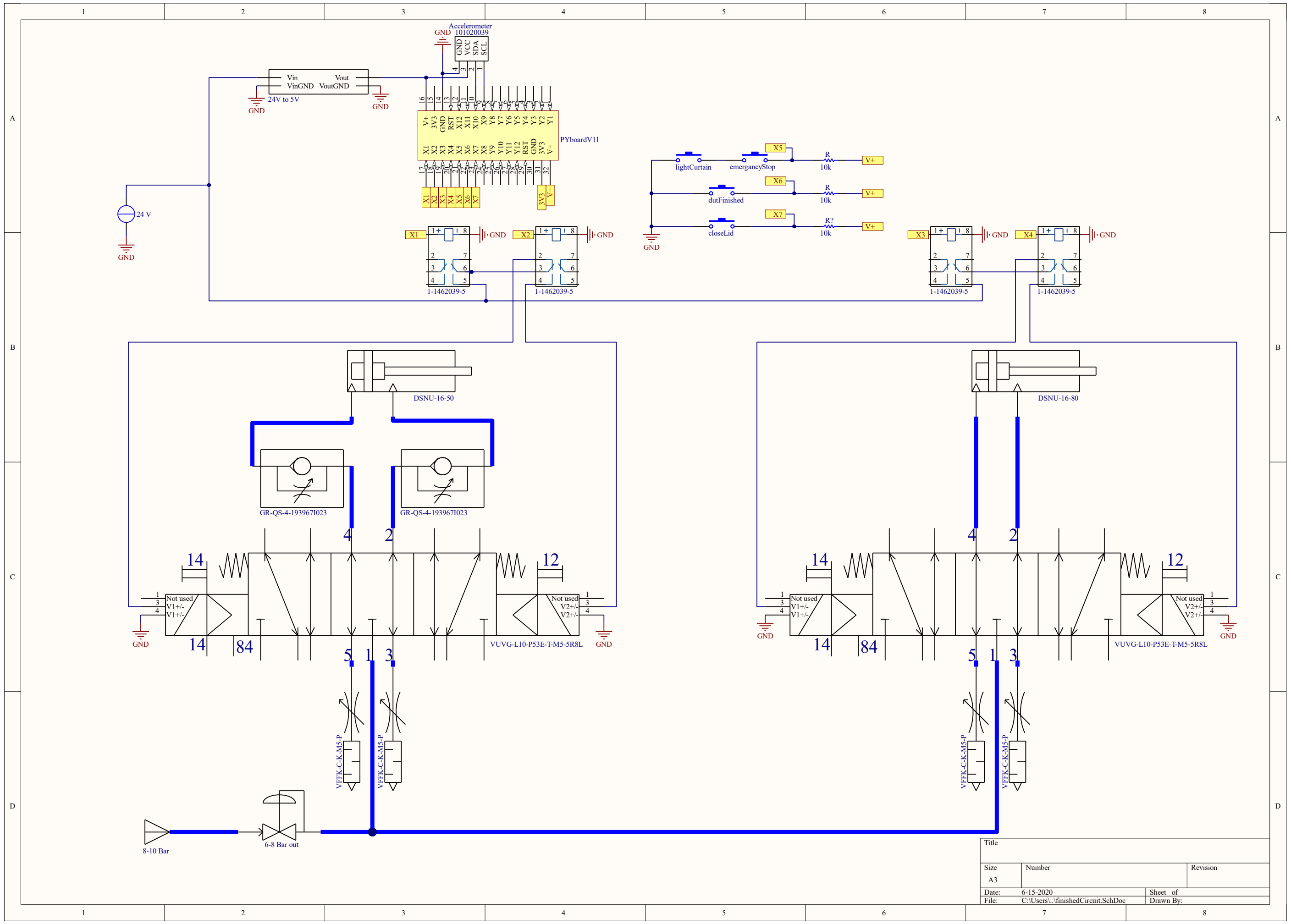


Figure 3.1: The final version of the circuit.

3.2 Mechanical implementation

The holder for the lower part of the lower cylinder was lathed in steel and the cylinder holder mounted to the lid and the handle was 3D-printed in ABS-plastic. 3D-printed parts have lower strength than parts made from aluminium or steel and using the 3D-printed parts in a factory would not last long enough (there are very strong materials that can be used for 3D-printing that might hold even in the factory, but finding such a solution is out of scope). Still, the 3D-printed parts were shown to be much stronger than thought and held very well for testing and demonstration of the solution. One benefit with 3D-printing the parts was the possibility to change design: printing one part took around 4 hours and is very low cost. A key measure to make sure that the threads in the 3D-printed parts would not be stripped was to use as long bolts as possible to let it catch many threads.

The biggest part of the cylinder holders was mounted using four M4 screws. It would be beneficial to have bigger screws than M4, but due to the tight margins this was the biggest screw size that could be used. After testing it was clear that M4 actually worked very well. One problem that quickly became evident was that the measure 34opened from figure 2.11b was shorter on the CAD-model than in reality. The CAD-model showed a length of 287 mm while the real model had a length of 310 mm. This meant that the lower cylinder was too short to let the lid fully open.

The other parts used to fasten the cylinders to the fixture (point 1 and 4 in figure 2.11b) were rigid enough even though the cylinder was mounted with single shear. The steel mount for the lower part of the lower cylinder was fastened with a M4 screw instead of M5 as the original idea was. The reason for this was that there would be too little material around the threads and the risk of the part to break was too big.

The forces that were calculated in section 2.6 were measured at the mounting points of the pneumatic cylinders and are shown in table 3.1.

Table 3.1: The tool used to measure the forces could maximum measure a force of 60 N. The force required to close the lid was greater than that.

Scenario	**Stage**	**Force [N]**	**Lid direction**
2 gas springs	**Locking/ Unlocking**	50.0	Unlocking
		30.0	Locking
	Closing/ opening	32.0	Opening
		60 (max)	Closing
No gas springs	**Locking/ Unlocking**	57.7	Unlocking
		2.0	Locking
	Closing/ opening	49.0	Opening
		49.0	Closing

It is important to notice that the lid, cassette and DUT were not placed in the box for this measurement. The reason being that they were not available at this point in time.

The aim with the testing that was done was not to test the durability of the parts and do the opening/closing sequence many times, but rather to see if everything worked and if some obvious errors would be encountered. This means that even if some parts seem to work well (for example, the points where the cylinders were fastened with single shear) during this testing it is impossible to know how the parts will hold during an extended period of time.

3.3 Pneumatic implementation

All the following components chosen for the pneumatic system are provided by Festo. They implement the standards "Safety of machinery – Prevention of unexpected start-up (ISO 14118:2017)" [20].

To regulate the pressure from 11 Bar down to 8 Bar the LRMA-QS4 from Festo was used. It is small, compact and the out pressure is adjustable.

The DSNU series of pneumatic cylinders from Festo seemed to be the most affordable and available option that suited the needs. The maximum forces needed from the cylinders (see section 2.6) determine the diameter of the cylinders. The specifications for the DSNU cylinders suggests a cylinder diameter of 16 mm for the lower cylinder and 12 mm for the upper [15]. It is easier to have the same cylinder diameter and it is better to be on the safe side so both cylinder diameters where chosen to 16 mm. In section 2.7.1 the stroke for the upper and lower cylinder needs to be at least 52 mm and 74 mm.
The upper cylinder must have a retracted length of 212 mm and an advanced length of 287 mm. DSNU-16-80 has a stroke of 80 mm, retracted length of 207 mm and advanced length of 287 mm when including the rod end (SGS-M6 by Fest) in the calculations. The lower cylinder must have a retracted length of 170 mm and an advanced length of 220 mm. DSNU-16-50 has a stroke of 50 mm, retracted length of 170 mm and advanced length of 220 mm, also here including the rod end in the calculations.

VUVG-L10-P53E-T-M5-5R8L by Festo was chosen to be the solenoid valve package. This package was recommended by Festo and implements the features that are needed: letting the pneumatic cylinder move in a damped motion set by the air restrictors, let the cylinder extend with a damped motion set by one of the flow restrictors or let the cylinder retract with a damped motion set by one of the flow restrictors. The solenoid valve package is controlled via two signal inputs. The input voltage and current required by the solenoids are 12 V or 24 V and 41.7 mA [23]. These values are important later when choosing relays.

When testing the pneumatic system an important problem was found. If the valve package was in the middle state and then moved to the right or left the air restrictors connected to port 5 or 3 would not slow down the cylinders motion as much as needed. To explain this let us consider the cylinder being fully retracted and the valve package being in the middle state and then changed to the leftmost state. In the middle state the pneumatic cylinder has approximately 1 Bar in both air chambers. When the valve package is set to the left state the left air chamber of the cylinder will be exposed to 8 Bar while the right air chamber has a pressure of 1 Bar. The pressure in the right air chamber is not enough to make the air restrictor connected to port 3 brake the air flow fast enough. This results in the piston accelerating very fast in an advancing movement. The first solution to this problem was to set the valve package in the state that the cylinder is already in. For example, if the cylinder is retracted and should be extended if the valve package was first set to the right state and then the left instead of going directly from the middle state to the left. This solution is a bit quirky and was replaced by the other solution. Simply placing an air restrictor in series with the input air to the cylinder will brake the motions no matter what pressure is already in the cylinder. This solution was only applied to the upper cylinder since there were only two restrictors available. It was not too big of a problem if the upper cylinders motion was not braked properly since the weight of the lid did not allow for rapid movements of the lower cylinder.

The biggest problem with the final pneumatic implementation was to control the closing of the lid: when the lid is fully opened and should be closed. What happened was that the lid stayed fully opened when both gas cylinders were mounted and the pneumatic cylinder could not pull the lid with a great enough force to close it or that the lid accelerated downwards uncontrollably when one of the gas cylinders were removed. There are two major problems that give this result.
The first is the force calculation. As mentioned in chapter 2.6 the measurements of the forces were done correctly throughout the full motion of the lid: from fully opened to fully closed and locked. The greatest force was chosen to design the cylinder after. The problem was that the calculations of the forces were done in the position closed but not locked and then assumed that the forces would be approximately the same for all positions of the lid. This was shown to be wrong for the lower cylinder as the force required to close the lid was much greater than the cylinder can apply.
The second problem is that the force needs to change direction when closing the lid. The cylinder would need to apply a retracting force and then an advancing force: when the lid is fully opened a retracting force is needed to overcome the gas cylinders, but halfway down the gas cylinders lose their force and can not hold the lid any longer. Here, the cylinder would need to change direction. This can not be done fast enough with a pneumatic cylinder since it takes some time to fill the cylinder with air. It was tried to manually change direction of the cylinder via a button, but as predicted the delay from the relay switching to the force changing direction was too big to control the movement smoothly.

3.4 Electrical implementation

The original idea was to implement the circuit on a PCB. Due to the ongoing pandemic, lack of resources and time the circuit was instead implemented on a stripboard. There were some clear downsides to using a stripboard instead of designing a PCB: it was much easier for solder grease and other junk to either short circuit two nodes or act as a capacitance between them. Using cables instead of copper lines made it possible for the cables to tangle and get stuck in other stuff leading to short circuit or circuit breaks. A properly made PCB also usually results in less noise and interference. The debugging of the circuit also became harder as it was much harder to get an overview of whether there are any short circuits than if a PCB would be used.

According to the datasheet of the pyboards MCU the maximum power that can be drawn from each Input/Output (I/O) pin is 25 mA and the maximum total current that can be drawn from the chip is 150 mA [5]. Since there will be four relays and $4 \cdot 25 < 150$ the maximum current that can be drawn from each relay is 25 mA. The relays that were found and chosen for this purpose are the 1-1462039-5 by TE Connectivity Potter & Brumfield Relays. This is a Double Pole Double Throw (DPDT) relay which is more than needed. It would be ideal to use a Single Pole Single Throw (SPDT) relay, but none with a low enough input current were found. The 1-1462039-5 has a signal current of 16.7 mA (below 25 mA), signal volatage of 3 V (the pyboard outputs 3.3 V), contact rating of 2A (the valves need 41.7 mA) and a switching voltage of 220 VDC (the valves run on 24 V). This relay satisfies all the needs and more.

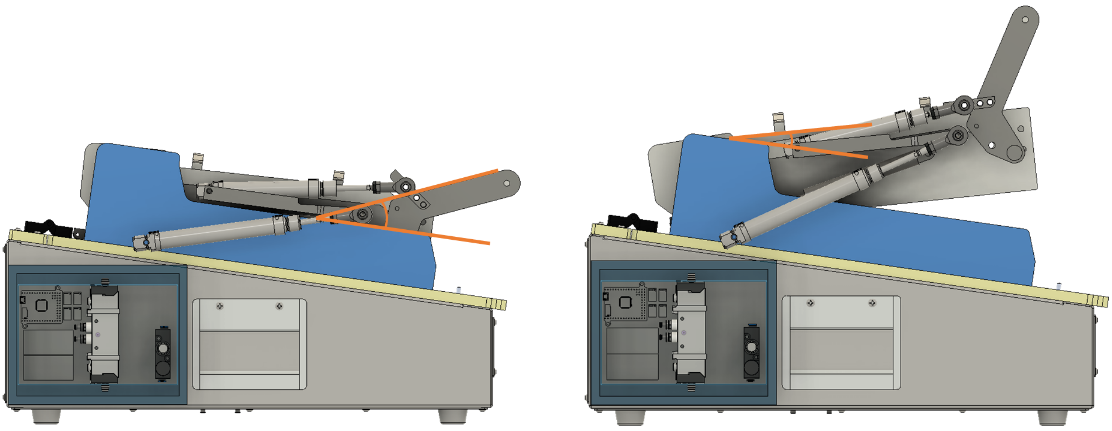
Due to lack of time the light curtains were not implemented and instead replaced with a button connected to a digital input representing them. The NUC was also replaced with a button signalling when a DUT is finished. The buttons are configured with a pull-up resistor. Using analog buttons connected this way results in a lot of so-called bouncing. This is taken care of in the software on the pyboard but is not perfect. Using an analog filter would probably give a better and more reliable result. The buttons were implemented in a separate circuit outside the box containing the main circuit and pneumatic valves. The card has six inputs: Ground (GND), 5 V, button1, button2, button3 and button4. The pull-up part of the circuit was also made on the buttons card. The fourth button is redundant but included in case it would be needed for debugging.

The accelerometer that was used was the same as the one already mounted to the pyboard: MMA7660. A version of this accelerometer placed on a development board was chosen: 101020039 by Seeed Technology Co., Ltd. When the circuit was tested, it quickly became apparent that the accelerometer had too low accuracy to be able to use for any accurate angle measurement. It worked fine to determine what position the lid was in (fully opened, closed but not locked and locked), but getting an accurate continuous angle from the sensor was hard.

3.5 Software implementation

The program was mostly implemented as described in section 2.5. Following is a description of how the angle measurement was implemented.

To be able to control the lid movement exactly the position of the lid must be known. It was not a goal to be able to control the lid movement exactly, but implementing position sensing with the accelerometer was tested and evaluated to know if it is a possible solution for the future. Angle measurements were done with increments of 5° using a protractor. For every angle that was measured the maximum and minimum x, y and z-value from the accelerometer were written down (the output from the accelerometer was shifting ± 1 output unit). This resulted in a table that could be interpolated. When a value from the accelerometer is given the corresponding value for the angle of the lid can be looked up and linearly interpolated if not exactly found. The positioning of the lid was divided into two motions: from fully locked to closed but not locked and from closed but not locked to fully opened. Figure 3.2 illustrates were the different angles were measured.



(a) The angle shown in the figure is the angle measured from fully locked to closed but not locked.

(b) The angle shown in the figure is the angle measured from closed but not locked to fully opened.

Figure 3.2

After testing the implemented angle measurement, it was clear that the accuracy was not sufficient. Even applying a moving average filter, a moving median filter, removing outlying values or different combinations of all the above the angle was still not very accurate. The main problem seems to come from the accuracy from the sensor. For example, having the handle at 0° gives an output of (x, y, z) = (2, 19, 5) to (4, 22, 4) and having the handle at 5° gives an output of (x, y, z) = (2, 19, 6) to (4, 21, 8). Some values overlap and this is the general trend throughout all the angles. It is possible to give a well angle output, but not accurate enough to use for continuous feedback. See A.3 for the full table of angles.

4. Analysis and discussion

4.1 Analysis and discussion of the results and implementation

The measured results and chosen implementation methods are compared and discussed in this section.

4.1.1 The mechanical system

The mechanical solution held up well. Even though the solution was printed in ABS-plastic it held well for the testing and code development. The fact that the threads did not get stripped on the plastic parts was above expectations. One benefit of using plastic instead of metal is that if something breaks it is the printed parts, not the FCT-fixture. If the 3D-printed parts break, they are easier to manufacture and have a lower cost.

when comparing table 2.3 and 3.1 it is clear that they differ. The biggest difference (such as in the rows "Locking/Unlocking, Unlocking" for both 2 and no gas springs in table 2.3 and 3.1) are probably due to the lack of the cassette in the later measurements. When locking and unlocking the FCT-fixture, the needles in the cassette provide a relevant force against the DUT. That force is measurable all the way out to the handle. The other difference between the two tables are probably due to that the CAD-model does not match the real model exactly which results in inaccurate angles and distances measured. The method used to measure the forces are not very accurate either and the fact that there was no lid, cassette or DUT placed in the box for these measurements results in less accurate measurements. The measurements are however good enough for designing the pneumatic cylinders. The only value that was miscalculated was the closing force needed by the cylinder when the lid is fully opened. It was not possible to measure that force since the force gauge used could measure a maximum of 60 N, but the calculations gave a force of around 200 N which is too much for the lower pneumatic cylinder. If the trend between measured forces and calculated forces are followed, the pneumatic cylinder would need a greater force than the 200 N calculated.

The miscalculations of the forces required from the cylinder and the mismatching measures between the CAD-model and real FCT-fixture are very basic mistakes that resulted in big faults in the solution. These mistakes show how important it is to have a second person go through the calculations and measurements continuously. It is an already known issue among many engineers that it is easy to miss the solution to a problem when it is right in front of you, but it is nevertheless very important to try not to do it.

It is never good to mount parts with single shear, but sometimes it is the only solution available. Because the design used a small lever the forces exerted by the cylinder did not break the mounting points. In this case there were no problems mounting the parts by single shear.

4.1.2 The pneumatic system

The pneumatic system worked well except for the closing of the lid. The idea was that the air flow restrictor connected to port 5 (see figure 3.1) would act to brake the acceleration provided by the lid's weight. The problem is that even if the output ports (3 and 5) are completely blocked, the pressure in the cylinder is not enough to brake the motion of the lid enough.

The force calculations for the fully opened lid were done with the lid's theoretical fully open state, not considering the slightly too short lower pneumatic cylinder. The fact that the cylinder is too short results in a smaller needed force from the cylinder, but even this smaller force was too great for the cylinder to apply.

4.1.3 The electrical system

The electrical design required for the chosen solutions was minimal. Most of the solution was in the mechanical part and the programming of the system.

Using an accelerometer for position measuring results in the system being sensitive to leaning. For example, the table in the factory might not be entirely straight resulting in different an output from the sensor. Of course, a calibration can be done at each start-up to eliminate this error or a second accelerometer fixed at the FCT-fixture's base could work as a reference accelerometer to eliminate possible errors, but it is still a very sensitive system. Using an accelerometer is a good solution, but probably not the best in this case.

4.1.4 The program

The filters implemented in the program was shown to be very helpful when taking measurements from the accelerometer. Outlying values were especially an issue which could be eliminated by simply removing them. To get a much nicer output signal the moving average and moving median filters did a good job. As mentioned, the debouncing filter for the buttons could have worked better, but it still did a well enough job for testing. Implementing the filters shows how powerful software can be: there were no analog filters needed to get the values filtered. This eliminates the need for more hardware and the risk of more components breaking. The digital filters are also very customizable and can simply be changed with a software update.

4.2 Improvements and further development

There were some parts that could have been improved in this project within the scope. There is also a big possibility for further improvements of the general concept since this solution is not a fully developed system. These areas are discussed in this section.

4.2.1 The mechanical solution

The mechanical part worked fairly well. The biggest problem was some faulty measurements of the FCT-fixture: the CAD-model of the fixture had some different measurements than the real fixture. This could easily have been prevented by double checking the measurements. An improvement is to adjust all errors in the model to make it match the real fixture.

As mentioned in section 3, the solution is designed without any real knowledge about how the parts would hold for thousands of opening and closing cycles. If this solution is to be used in a real factory the design must either be tested for many cycles or the forces acting on the manufactured parts calculated or simulated. The forces that the screws provide must also be calculated to predict how long they will be able to hold the manufactured parts in place.

For the next iteration of this project it is important to consider which materials the parts should be made of in the factory and how they should be manufactured.

4.2.2 The pneumatic system

One design solution that was missed during the design process was to use the electrical servo converted to a linear motion (see A.5). This solution would take up a bit more space and probably cost more but has some other benefits. The position sensing of the lid did not work well enough to use in any closed loop regulation with the accelerometer. Some electrical linear actuators have built in position sensing which could be used to, more accurately than using an accelerometer, determine the position of the lid. The electrical servo motor can change direction faster than the pneumatic cylinder. These two factors combined means that using the right electric linear actuator would enable the possibility of controlling the exact position of the lid and most importantly it would be possible to close the lid without it smashing down destroying bearings and making the pinching risk much greater. It is also beneficial to skip the pneumatic input power and only use 24 V as input.

If the pneumatic system is going to be used in the future, Electrically controllable air flow restrictors placed in series with the input air to the pneumatic cylinder would make the system better. Being able to control the air flow with the pyboard enables a lot of functionality.

4.2.3 The electrical system

Further development of the electrical system would first and foremost be to design and manufacture a PCB instead of using an ordinary stripboard. That would probably eliminate bad connections and the problem with communicating to the accelerometer via I^2C would probably not be interrupted as easily. Short circuit and unwanted capacitance due to grease or dirt between the nodes would also be less of a problem. A big benefit with using a PCB instead of a stripboard is that most of the components could be chosen to be much smaller. This was not very important for this thesis, but might be in the future when the whole mechanism should be fitted inside the FCT-fixture instead of in a box mounted outside.

It is important that the button debouncing works properly, especially for the emergency stop button. The debouncing that was implemented is discussed more in section 4.2.4. Implementing analog debouncing on the buttons is one solution that could have worked better. The capacitors used on PCBs are generally very small and would not take up much excess space. The benefit is that the pyboard would get a clean signal directly and the code would be easier to understand.

The accelerometer used did not have good enough accuracy. One solution is discussed in section 4.2.2, but another solution could be to try more accelerometers with greater accuracy. There are many accelerometers with varying accuracy communicating via I^2C available.

Implementing light curtains and testing them is basically the next step of the solution and absolutely included in further development. The theory of implementing light curtains have been investigated in this thesis, but there is a big risk that unexpected problems will be evident when implementing them.

The interface towards the operator must be refined if the solution should be implemented in a real factory. The stop button must fulfill all standards and the rest of the interface should be easy to follow and have good instructions.

4.2.4 The program

As mentioned earlier, the debouncing of the buttons was not implemented as well as it could have been. There are several algorithms that can be used to implement debouncing. In the future some other algorithms should be tested and evaluated. Combining analog debouncing with debouncing in the program might also show to be a good solution.

If the light curtains are implemented and the hardware works properly it can be used for much more than just stopping the ongoing motion. As IR proximity sensors can measure distance this information could be used to program the movement depending on how far away for example the operator's hand is from the lid.

If an electric linear actuator was to be used instead of the pneumatic cylinders a Proportional Integral Derivative controller (PID-controller) could be implemented. This would enable the exact control of the lid's movement. The electrical linear actuator can also feed the torque from the electrical motor back to the pyboard. This gives the possibility to have one more safety solution by measuring the torque and checking so that it is not greater than it should be.

If the accelerometer is going to be used for position measurements in the future the next step would be to implement automatic calibration of the accelerometer.

As mentioned earlier, it is not guaranteed that the table where the FCT-fixture is placed is going to be exactly perpendicular to the gravitational force. The FCT-fixture might be moved from day to day and the calibration should therefore be done at every start-up.

5. Conclusions

How difficult is it to open and close a lid? Apparently more difficult than first thought. The results of the project show how difficult it is to implement a simple idea in real life. The work done to reach the results is only one part of the work needed to implement a fully working solution and only a fraction of the work needed to get the full solution safe according to all harmonized standards. Hopefully this project has provided Mikrodust with a good starting point for developing a fully working solution.

The prototype built was far from fully working, but some parts worked well. The locking and unlocking of the lid worked well. Using the accelerometer as a limit switch also worked well (neglecting the communication problem via I^2C). The cylinder used for opening and closing the lid could work if the built-in gas springs where switched to a pair with carefully chosen forces and the weight of the lid would e adjusted to exactly the right weight. However, even if the mechanism would work in this case it should be possible to change cassette, insert in the lid etc. without inhibiting the movement. Replacing the lower cylinder with an electrical linear actuator would probably be the best step for next iteration.

The massive work of reading up on and implementing standards should not be underestimated. Even though the standards were fairly well understood it was very hard to include them in the technical solutions. This is also a great example of why at least two engineers working on one project is better than one. Generally, this project includes a lot of different areas and dividing them between two engineers would probably give a more thoroughly thought through design choice and implementation.

The most important conclusion and lesson is that it is better to fail several times than to over design one solution. It would for example be much better to implement the first chosen solution, test it, observe what does not work with it and then iterate with another improved solution. This is a faster method, but also costs more in the short run. The pros and cons need to be taken into consideration to know where to draw the line between fast development and saving money on hardware.

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A. Appendix

A.1 Standards

"Safety of machinery – General principles for design – Risk assessment and risk reduction (ISO 12100:2010)" [11]

The relevant sections in [11] are:

- 4 Strategy for risk assessment and risk reduction
- 5.3.2 Use limits
- 5.5.2.3.3 Possibility of avoiding or limiting harm
- 5.5.3.4 Human factors
- 5.5.3.6 Possibility of defeating or circumventing protective measures
- 5.5.3.7 Ability to maintain protective measures
- 6.1 General
- 6.2.9 Electrical hazards
- 6.2.11.3 Starting/stopping of a mechanism
- 6.2.11.6 Use of automatic monitoring
- 6.3.2.2 Where access to the hazard zone is not required during normal operation
- 6.3.2.5 Selection and implementation of sensitive protective equipment1)
- 6.3.3.2 Requirements for guards
- 6.4.5 Accompanying documents (in particular - instruction handbook)

A.2 Circuits

Table A.1 shows what valves are used depending on the input.

Table A.1: The principle is the same for both valve packages shown in 2.6, hence the input values are shown as for example X1/X3 instead of only X1.

X1/X3	**X2/X4**	**Valve position**
0	0	Middle
0	1	Middle
1	0	Left
1	1	Right

A.3 Angle measurement with accelerometer

Table A.2: The measured values are under the first output column and the average of the maximum and minimum values are under the second output column. The sensor outputs a value between -30 and 30 where 30 corresponds to 1.5g and -30 corresponds to -1.5g.

Angle of the handle [°]	**Output [$\frac{1.5}{30}$g]**						**Output [$\frac{1.5}{30}$]g**		
	Min	Max	Min	Max	Min	Max	Average		
	X		Y		Z		X	Y	Z
Handle									
-8	2	4	20	22	2	4	3	21	3
0	2	4	19	21	5	6	3	20	5.5
5	2	4	19	21	6	8	3	20	7
10	2	4	18	20	8	10	3	19	9
15	2	4	17	19	10	11	3	18	10.5
20	2	4	16	18	11	13	3	17	12
25	2	4	15	17	13	14	3	16	13.5
30	2	4	14	15	14	15	3	14.5	14.5
35	2	4	12	14	15	16	3	13	15.5
40	2	4	11	12	16	17	3	11.5	16.5
45	2	4	9	11	18	20	3	10	19
50	2	4	6	8	19	20	3	7	19.5
58	2	4	4	6	19	21	3	5	20
Lid									
-1	2	4	5	6	19	20	3	5.5	19.5
5	2	4	2	4	20	21	3	3	20.5
10	2	4	1	2	20	22	3	1.5	21
15	2	4	-2	0	20	21	3	-1	20.5
20	2	4	-3	-1	20	21	3	-2	20.5
25	2	4	-5	-3	20	21	3	-4	20.5
30	2	4	-7	-5	19	20	3	-6	19.5
35	2	4	-9	-7	19	20	3	-8	19.5
40	2	4	-11	-9	18	19	3	-10	18.5
45	2	4	-12	-11	16	18	3	-11.5	17
50	2	4	-14	-12	16	17	3	-13	16.5
55	2	4	-15	-14	15	16	3	-14.5	15.5
60	2	4	-16	-15	14	16	3	-15.5	15

A.4 Bill of materials

Table A.3 shows the bill of materials.

Table A.3: Bill of materials. The components that are not specified with a model number are components that were taken from the workshop and has no more important specifications than what is written in the "Component" cell. All components except "IR Long-range proximity sensor" were used.

Component	Amount	Modell number
Pneumatics and hardware		
Pneumatic cylinder upper	1 pc.	DSNU-16-80-PPS-A
Pneumatic cylinder lower	1 pc.	DSNU-16-50-PPS-A
Controlled valve	2 pc.	VUVG-L10-P53E-T-M5-5R8L
Controlled valve cable	4 pc.	NEBU-M8G3-K-2.5-LE3
Air restrictor-controlled valve	4 pc.	VFFK-C-K-M5-P
Rod end cylinders	2 pc.	SGS-M6
Pressure regulator	1 pc.	LRMA-QS4
Valve to thread connectors 90 deg	4 pc.	QSML-M5-4
Valve to thread connectors	5 pc.	QSM-M5-4
Valve to valve connectors 90 deg	1 pc.	QSML-4
4 mm air hose	2 m	PEN-4X0,75-BL
Enclosure	1 pc.	PC 150/75 HT ENCLOSURE
30 mm M6 screw	4 pc.	
40 mm M4 screw	5 pc.	
10 mm M4 screw	1 pc.	
5 mm m2.5 screw	2 pc.	
Electronics		
Mikropython PY-board V11	1 pc.	
Prototype PCB	1 pc.	
Voltage regulator	2 pc.	QS-2405CCBD-3A V1
Accelerometer	1 pc.	101020039
Relay	4 pc.	1-1462039-5
Accelerometer connector on card	1 pc.	110990030
Accelerometer connector cable	1 pc.	110990038
IR Long-range proximity sensor	4 pc.	GP2Y0A710K0F
Jtag 12 pin connector male	1 pc.	
Jtag 12 pin connector female	1 pc.	
Jtag 10 pin connector male	1 pc.	
Jtag 10 pin connector female	1 pc.	
Barrel power connector	1 pc.	

A.5 Electric linear actuator

An electric linear actuator works similarly to a pneumatic cylinder, but is using electricity as input power instead of pressured air.

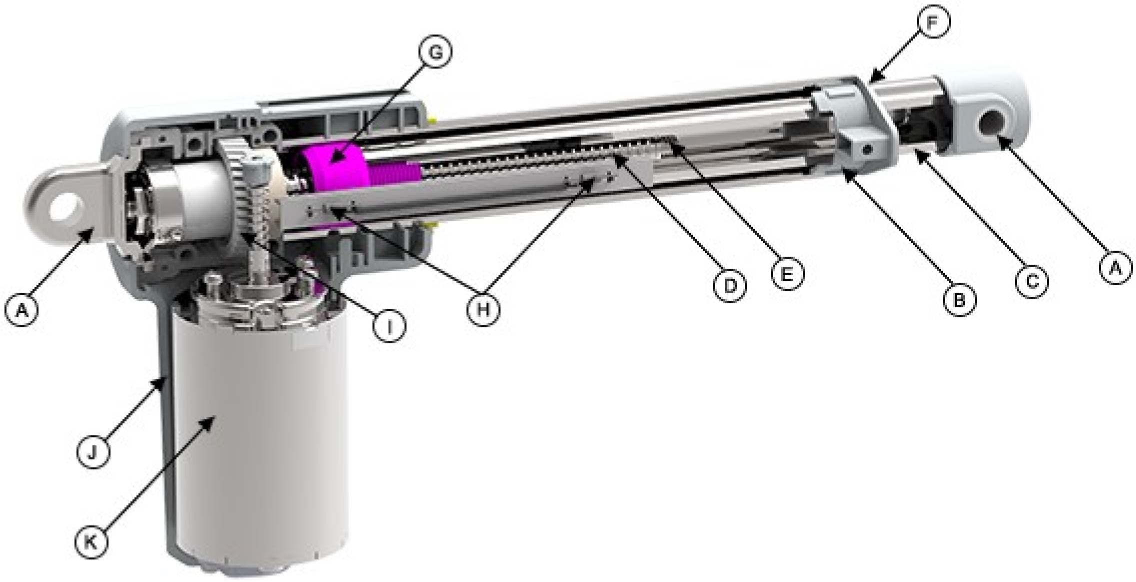

Figure A.1: Se through image of an electric linear actuator. [19]

The electrical motor is located at the end of the cylinder and the rotational motion of the servo motor is converted to linear speed with the help of a gear (I in figure A.1 above).