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Toni Heikkinen

Design Process of an Electric Shutter

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This thesis presents the design process for an electric shutter system. The electric shutter is a vital safety precaution for the measuring device, which the partner company manufactures. The measuring device uses a concentrated light source to measure the number of studied subjects going by the device. Most common application for this measuring device is in industrial exhaust stacks, where the temperatures can rise higher than electronic components can handle. Successful measuring requires a see-through hole into the measuring medium to get reliable results. The shutter unit protects the device by closing the hole, when needed.

Before starting the design process, the desired requirements set for the system and requirements set by the designed operational environment, were stated. The most notable environmental factor affecting the device is temperature. Electrical components have maximum temperature limits for reliable operation. The operation of the electrical shutter on an electrical actuator, which will generate a certain amount of the electricity need. The system also requires an indicator for the unit to enable autonomous operation.

The design process started by studying the target location inside the measuring device in a 3d modelled version. The parts were then modelled using the Autodesk Inventor software. After the models reached a certain point, prototype versions were 3d printed using a 3d printer. Plastic 3d printed parts were used to test the overall functionality of the unit and the design choices.

The goal for the thesis was to design an electrically operated version of the shutter unit, and this goal was achieved after 3 different prototype versions. The chosen prototype version is ready to be tested more thoroughly with correct materials and environment, to reach the commercial version of the unit.

Keywords	product design, measuring device

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1 Introduction

The goal of this thesis was to design, analyse and test different options to find out the possibility to upgrade the mechanical functionality of the shutter unit in Company Oy's measuring devices. Company Oy's measuring device rely on laser attenuation measurement method. In order to quantify the number of particles going past the device, the laser requires an obstacle-free pathway through the measuring medium.

The most common use for the measuring device is to measure particle flow in industrial exhaust stacks, which means that there needs to be a hole in the stack. The shutter plays a crucial part in protecting the measuring device from high temperature and possibly corrosive stack gases, by shutting down the clearance hole when needed. The product design was executed due to requests from different clients for such an add-on. As for the features this add-on provides the ability to remotely observe and control the position of the shutter is most desired by clients.

For business economic reasons, this thesis contains confidential information about the Company Oy's products and the design of the shutter, the identity of the company and some parts of the thesis is hidden from public, and the company is referred to as Company Oy. Company Oy is a privately-owned company situated in Finland with decades of experience in the industry. They design and manufacture different types of measuring devices, and their clients are located all around the world. In addition to their own line of products, they are a reseller for even wider range of different kind of measuring devices.

2 Working principle of the product

The product has been designed to measure particle flow in a stack. The method for detecting the particles uses a beamed laser through the desired measurement medium. The complete product consists of 2 units, which are transmitter and receiver units located on opposite sides of the flow medium. The most common measurement medium is particle flow inside of an industrial stack. Many different industries can benefit from this device. The most common applications for a device measuring the amount of particles are in power industry, metal manufacturing industry, fuel industry and agricultural industry [1].

Product functionality is described in more detail in Appendix 1.

3 Design requirements and goals

The goal for this development project was to analyse and test different options to study possibility to upgrade the mechanical functionality of the existing shutter solution. The new version of the shutter unit improves the reliability and customer experience, as the position of the shutter can be monitored remotely, for example from the control room. The designed operating environment set requirements for the electric shutter, which needed to be asserted in the design process. The overall design goal was to produce a high-quality fail-safe solution for Company Oy’s product. Most important factor affecting the freedom of design, was to have the electric shutter be as far compatible with the current version of the product, as possible, to enable existing customers to purchase it as an upgrade for their device using the previous version of the shutter. Additionally, the design solutions were made in a way where the manufacturing process uses materials as efficiently as is reasonably possible, i.e. minimizing the amount of waste material produced also minimizes the carbon footprint for the whole lifecycle.

3.1 Temperature

One of the most important factors affecting the design and the selection of raw material is temperature. As the measuring devices are possibly mounted on high temperature stacks, the device needs to be able to withstand heat to a certain degree. This means that the electric shutter also needs to be designed to withstand a high temperature range. This mostly affected the placement of the motor, as it is possibly the most heat sensitive instrument in the design of the electric shutter. The design for the electric shutter also takes account for much higher temperatures, as the shutter is directly in contact with the environment inside the stack. In normal operation, when the valve is open, the passing air cools down the device, but when the valve is closed, the air stream does not provide cooling anymore, and the stack side of the shutter chamber may be exposed to high temperature. Company Oy’s goal is to produce robust products, which can handle the harsh environments where they are designed to operate, without losing valuable lifetime of the product.

3.2 Pressure sensing

In order to achieve an autonomous operation, there needs to be a way to sense the pressure on the inside of the device and on the stack side. The value of pressure is measured from different sides of the shutter valve to determine the current direction of the flow for the instrument air. Air flow needs to be directed out of the transmitter especially when measurement medium presents high temperatures, corrosive gasses, moving dust or higher pressures. In other terms, the delta value between the inside and the stack side pressure values must always be positive. This information is read by a microcontroller which controls the motor unit used to close the shutter valve. The other factor affecting the pressure sensing design needs, is the fact that the actual sensors are heat sensitive and do not tolerate high temperatures, which causes the physical placement to be considered accordingly. The latter limitation is possible to circumvent by using appropriate methods, which are discussed later in this thesis.

3.3 Electricity need

The older version of the shutter had the benefit of functioning properly even during an electric black out. As one can quickly understand, the motorized shutter needs electricity to function; therefore, the design must include a battery solution, consisting of the actual battery and management/charging circuitry for it. The initial idea was to have a separate electronics box inside the product's casing, where the control circuitry and batteries would be located. The requirements for the battery's characteristics are long reliable lifetime, low self-discharge rate, decent amount of capacity to keep the shutter unit operational for even prolonged periods of time, and to have enough current output to run the servo motor flawlessly. The battery should also withstand colder/hotter temperatures into a degree, for scenarios where the measuring device is located outdoors, and where the temperature could even go below zero. Common knowledge of how well batteries can handle cold is that they do not do it so well. Lower temperatures can decrease the available performance of the battery [4].

3.4 Compatibility with the previous version

As the electric shutter is meant to be an update of the old shutter, the design was approached in a way to make it as compatible with the current measuring device design as possible. In other words, the available space where the shutter needs to fit, is somewhat limited. This greatly affects the selection of the right motor, as the motor needs to be relatively small, but still has enough torque to counter act pressures from the stack and keep the measuring device insulated if needed.

3.5 Motor

The actuator, in this case the motor, which moves the shutters gate, needs to have a reliable method of controlling it, to guarantee proper gate operation. Suitable motor type for this situation is a servo motor, as they can be accurately controlled, they hold their position and can generate some amounts of force. Unfortunately, the industrial servo motors are too large to fit this project properly. Therefore, it was decided to use high end RC aircraft servo motors. The idea of using hobby grade parts, does not sound very appealing, and increases the need of extremely thorough stress testing, to ensure long enough lifetime for the device. The suggested servo model selection is discussed with supporting calculations in the product design chapter.

Speaking of reliable operation and long lifetime, the design needs to be made in a way that prevents possible dirt accumulation in places where the sealing ability of the shutter may be compromised. The instrument air coming inside the device is supposed to be filtered, and if the client is using Company Oy’s blower units, the air purity is guaranteed with a 1-micron filter. The shutter needs to be designed in a way that takes advantage of this airflow as a cleaner, to decrease the maintenance need. Inside the shutter chamber there needs to be enough space for the possible dirt coming from the stack not to accumulate in a way that prevents the motion or sealing ability of the shutter.

3.6 Design goals

The main goal for the design was to find a way to manufacture a reliable, high quality and robust shutter solution with low manufacturing costs. Also, the parts that require machining or different outside the house production methods, are designed in a way which considers the limitations of the used machinery, lowering the production costs, as the parts are easier to create. As we are dealing with air pressures acting on several different directions and surfaces, the total sum of area for these surfaces are being kept as small as possible, thus lowering the actual forces that the motor unit must deal with.

Smaller forces cause less unnecessary stress to the motor, which in long term translates into more reliable operation and longer lifetime of the servo, before replacement is needed.

High quality of the product is ensured by using only trustworthy machining companies, and by carefully inspecting every received part, which all need to meet the quality standards set by Company Oy. Inspection also ensures the reliability of the product, as all the failures caused by manufacturing errors, either in the machining or impurities in the materials itself, can be detected before the assembly, and therefore they can be eliminated.

4 Design process

The next chapter goes through the different versions of the electric shutter's design from the first prototype to the final version. The purpose of this chapter is to explain the design choices made and how the design changed on its way to the final version. Additionally, used software and other design aids, are introduced in this chapter.

4.1 Design tool

In today's world of product design, CAD software's are a crucial tool for the product design process. Computer Assisted Design programs makes designing more complex systems far easier than hand drawn designs.

The design for the electric shutter was completely made by using Autodesk Inventor. All 3D models and drawings are possible to make under the same software, as explained more thoroughly in the next chapter.

4.1.1 Inventor Professional 2019

The reason for choosing this CAD software over other eligible choices, was mostly the fact that the company had already used this software for years and because Autodesk offers free licenses for students, allowing designing remotely from home pc, which increased the possible time available for the design process. The fact that the measuring device was already 3D modelled, and this model was available for use in correct file format (with all the smart features included) decreased the modelling time significantly, as the design for the electric shutter could be started straight away straight into its desired position using Inventors Assembly Feature.

As the name suggests, the Assembly mode allows to handle multiple 3D models (parts) as an assembly and attach/constrain the parts into each other. Easier said, the assembly mode allows to virtually construct the device from its components. Creating new components which are dependent on other components dimensions is surprisingly easier and faster with the Assembly mode, as you can create the part straight into its place and measure dimensions of the other components straight in same window.

Individual components can be edited in the Part mode, where only one 3D model is opened and viewed at a time. This allows to have a better view of the model, as other parts are not present nor therefore visible. After having done the initial modelling in the Assembly mode, the later minor tweaks and corrections can be done in Part mode. The Part mode also allows the user to use the 3D print feature, where the orientation of the part can be changed easily, and it can be exported as a STL-file (which is a standard for the slicing software of the 3D printer). The ease of orientation change is quite handy as it affects the way the part is printed.

After the parts are completely tweaked and are ready to be realized, the Inventor uses the Drawing mode, which is designed to layout the dimensions of the part. This mode allows exporting in PDF format, which is rather universal document format, meaning that the assigned metal workshop can easily read it. Even though most workshops require a 3D model in their preferred file format, 2D dimensions in pdf format can help the communication between manufacturer, as side notes and things to consider can be written in normal text into the drawing. The paper version of this drawing will be archived physically in the company's site to act as an ultimate backup, in case of a data loss.

4.1.2 File handling

Scenario where data loss would happen could be critically crippling for this thesis causing loss of valuable time, and in worst case scenario in loss of design ideas and features. As an example, a hard drive failure could render all the cad files unusable and cause them to disappear into thin air. Another realistic scenario is a malware attack, more specifically malware called ransomware, which is a cyber-attack designed to extort money from computer users by encrypting all the files inside the system. In order to open the encryption, the victim is asked to pay some amount of money to the attacker, who will then provide the encryption key which removes the encryption from the system. Another option in an ransomware attack is to format the hard drives (delete all the files). This gets rid of the encryption, but also all the personal files are lost during this process. To prevent such scenario from happening, a back-up plan was created before starting the design process.

The most efficient method to protect your files from previously stated scenarios, is to use a cloud based back up system. (What is cloud) Uploading your files to cloud, gives you one more safety barrier against data loss. For this project, Google Drive was chosen to be the cloud storage system for all the relevant files. The drive was setup to automatically synchronise files from the pc to the cloud every single time changes to files were made (uploads automatically to the cloud right after pressing save button in Office Word). In addition to using Google Drive, written documentary was also synchronized with OneDrive platform. OneDrive is Microsoft's cloud storage service, which plays very well together with their other software, e.g. as in our case with Microsoft Word. OneDrive enables to setup an autosave function, which as the name suggests, automatically saves the documents after every change (keeps the file synchronized almost in real-time with writing).

As an additional precaution, all the files were uploaded manually to the same Google Drive and onto a physical USB-memory stick, just to be sure. The manual back up was done once at the end of every working day. Sometimes Autodesk's assemblies' encounters errors if the files are just copied and moved to other directories. This why the Inventor has an export feature called Pack and Go. Pack and go creates a new assembly file and a folder, where all the dependent files are copied and moved, and all the hierarchies are constructed from beginning to match the Pack and Go assembly. This means that all the necessary files are gathered under the same directory. As an extra, the pack n go allows to pack all the files and compress them inside an archive (zip-file). Compressing the assembly files into one makes the manual back up process simple and easy, as only one file is required to move around. Unpacking this file gives a fully functional assembly file, with all the individual model files (ipt-files).

4.2 Prototype Versions

Prototype versions of the electric shutter were made to experiment with the functionality and dimensional accuracy. These versions relied on using 3D printing technology, which enabled fast and easy way to manufacture the parts. Fast means that all the possible changes could be modelled and tested in a matter of hours, as opposed of using metallic machined parts, which can take several weeks to manufacture, depending on the metal workshops work queue and such alternative factors. All thought 3D printers use plastic as building material, it is still suitable for early phases of testing, where the overall functionality of the design is under development. Sometimes problems related to dimensions and internal fitting of the parts do not show that clearly in the virtual environment of the Inventor; thus, having a physical and accurate prototype model helps tremendously to further develop the design.

All the major versions ready for closer inspection were 3D printed. The cost of using a 3D printer for prototyping is relatively cheap. The used filament PETG costs around 43 €/kg [5]. One prototype version, including all the printed parts, weight was measured to be 26g. Printing material cost can be calculated as follows: 0.026kg x 43 €/kg, resulting in a price of 1,2€.

4.2.1 Used printer and printing parameters

In this thesis project, the 3D printer of the thesis author was utilized. The printer is a custom modified version of a standard commercial FDM 3D printer. It is capable of printing filaments that require a maximum of 300 Celsius extrusion temperatures. The FDM stands for fused deposition modelling, meaning the model is printed in layers.

4.3 Selected servo motor

In order to be able to model and design the shutter, knowing the dimensions and properties of the servo unit is required, which is why the servo unit was selected in the first stages of the design. First selection criteria were the physical size of the servo. In order to make the electric shutter compatible with existing parts of the opacity monitor, the servo motor needed to be as small as possible. Another important selection criterion was the torque output of the servo. The largest force acting against the servo, would be the air pressure from inside the stack, when the shutters gate is closed. The estimated amount of force pushing the gate can be calculated, if the quantity of air pressure and the surface area of the gate exposed to the pressure, is known.

Comprehensive study on different servo models from different manufacturers found one model which was matching the size requirements, with promising performance specifications. The manufacturer is Turnigy, and the servo model name is TGY-811. The TGY-811 is slim shaped, metal geared digital servo. It can generate 8.2kg/cm of torque at 6 volts, and its dimensions are 30mm x 10mm x 35. [6]

At this stage of the design, we can only estimate the final surface area of the shutters gate that will be in contact with the air pressure when it is closed. The estimated diameter for the clearance hole required by the laser, is 10 mm. Knowing that surface area of a circle is

$$A = \pi r^2,$$

where r = 10mm / 2, results in surface area of A = 78.54 mm^2. The advertised torque from the servo was 8.2 kg/cm (the servo can generate 8.2 kg of torque per centimetre away from the centre of the rotating axis). With this information we can calculate the approximate maximum air pressure that the servo can handle, using following equation:

$$F = P * A \rightarrow P = \frac{F}{A},$$

where F = force, P = pressure and A = surface area. Inserting the known values into the equation, gives the following result:

$$P = \frac{8.2\ N \cdot m}{78.54\ mm^2} = \frac{8.2\ N \cdot m}{7.854 * 10^{-5}\ m^2} = 104\ 405.4\ N \cdot m/m^2.$$

Converting 104 405.4 N/m^2 to millibars gives a theoretical maximum pressure of **1044.054 mbar**. Knowledge based on the previous version of the shutter (non-electric) was used to state that the torque from the servo unit is enough but testing the capabilities of the servo in practice is recommended.

As now we have information on the power output, and the surface area of the gate can be estimated from 3D models, we can calculate the maximum air pressure that the servo can theoretically handle when the shutters gate is closed.

4.4 Controlling the prototype unit

The testing and controlling the motor unit was put into practice by using Arduino UNO microcontroller. Arduino is a microcontroller in a form which suits prototyping scenarios extremely well. “Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards can read inputs - light on a sensor, a finger on a button, or a Twitter message - and turn it into an output - activating a motor, turning on an LED, publishing something online. (Arduino.com, 2019) [21].

4.5 Prototype version 1

Introduction for the framework of the design can be found in Appendix 1. Prototype version 1 experimented with gears as a mechanical energy transfer method. The pros for using the gears are long lifetime, good power transfer efficiency from the servo to the shutter gate and accurate control. The largest downside about geared design was the amount of space the gears required, which can be seen in Picture 1.

Picture 1: Rendered draft model of geared version of the shutter.

At this stage of the development, the focus was set on finding the right way of interacting/moving the shutter gate. The gear assembly needed space, which required non-insulated clearings for the gears to go inside the measuring device, where the servo is located. This design required another sealing surface, to seal and protect the insides from the stack gasses. The new insulator surface was created by adding a protective cover on top of the shutter box, which is visualized in Picture 2.

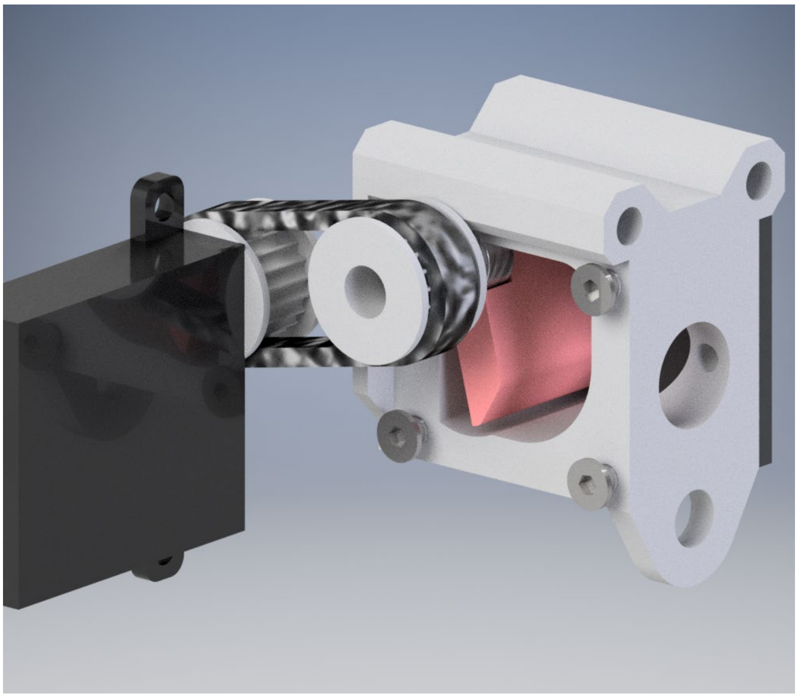
Picture 2: Rendered model of the protective cover.

The pressure sensing was implemented by drilling and threading two M3 sized holes to both sides of the shutter gate (the stack exposed side and the device side). The pressure measurement happens from the same hole which the laser uses to travel through. The M3 holes are used to connect 6 mm dia. pneumatic hoses with M3 connectors. The hoses are then run inside the device, where the sensors are located in safe temperatures.

As can be seen from Picture 2, the gear assembly requires quite much space. To make the geared connection feasible, the servo motor needed to be installed in the “hot” side of the device’s installation flange. As stated in the design challenges chapter that specific side may be exposed to much more higher temperatures than the set operating temperature for the device (-40 ºC to +60 ºC). This is one of the major reasons for abandoning the mechanical gear version, as the servo motor’s lifetime expectancy could have been severely impacted by the possible occasional high temperature exposure.

4.6 Prototype version 2

The heat caused the design to change to a version where, the servo motor is not placed in the hot side of the installation flange, but rather on the inside of the device. This solution required changes to be made into the installation flanges design; therefore, it is not fully compatible with the current device design. However, to ensure reliability and to fulfil the needed operating hour expectancy, the servo motor could not be positioned in its earlier place. By, moving the servo to inside the transmitter box, the servo is not directly exposed to high temperatures in normal situations. The different location for the servo also made the geared version obsolete, as there was no way to get the gear connection from the servo to the shutter valve, without doing major changes to the current product design. One possible solution for this was to use a timing belt to transfer the motion to the shutter valve. Picture 3 shows the timing belt connection from the servo motor.



Picture 3: Illustration of belt version draft.

To get the belt to run from inside the device enclosure to the outer side of the flange, a rectangular hole was needed to be made into the installation flange. One of the cons for this (and for the geared version), is the fact that in order to get the movement from outside of the shutter box to the gate, there needs to be a hole for the axle, and the axle hole needs to be sealed. In this size range of axles (4mm), sealing the axle successfully appeared to be a little bit tricky, as not so many properly fitting seals for this small application could be found.

Another concern caused by this design was the belt tension. Slack in the belt causes inaccuracy over time when moving the shutter valve, and because belt would be in a high temperature environment possibly for extended periods of time, it could possibly loosen faster than desired over time, increasing the maintenance need and shortening the interval between maintenances.

To overcome all these cons presented by the belt and gear versions, the design for the transfer of servo motion to shutter valve, changed to a magnetic joint version.

4.7 Prototype version 3

The third prototype version uses magnetism to transfer the energy to desired destination. Magnetism solution meets perfectly this project's needs, as it solves many of the concerns in the design. The design of the prototype version three makes the shutter's overall reliability much higher, as the motor is now protected from the environment. The required number of sealed surfaces are also lower, and the remaining surfaces can be sealed using simpler design solutions. The new design requires thorough testing in normal and challenging situations to be accepted to the consumer version of the product.

More in depth introduction for the prototype version 3 can be found from Appendix 1.

Prior to this point, the pressure sensing was supposed to be done by using M3 threaded holes in the shutter base frame. Pneumatic M3 connectors would have been attached to those holes and, from there the pressure would be transferred via hoses to the inside of the main devices case, in order to protect the pressure sensors from stack gasses and from high temperatures.

During testing the 3D printed prototype version, the tubing system seemed to add too many individual parts, thus making the complete system less reliable, as there are more possible weak points. Another factor affecting the reason for abandoning the tubes was the idea of using integrated/machined chambers inside the shutter's side cover. This solution reduces the individual parts needed for the device and makes maintenance easier as the shutter can be removed in one piece from the device. This also reduces time needed for initial assembly, cutting down needed man hours slightly.

The new airflow sensing route is done in a way, which minimizes the malfunction or faulty readings in the sensor caused by dirt blocking the airway. The machined groove has five individual smaller holes, to keep the air flowing even when some of them gets blocked. This groove design utilizes holes already present in the shutters base, which can be used to connect the pressure sensors to the target air space.

4.8 Back-up power solution

The back-up battery system ensures that the electric shutter stays operational, even when the device is disconnected from supplied power for any reason. Detected power outage triggers a fail-safe mode in the shutter, which closes the gate to prevent any damage to insides. As an additional precaution, the shutter gates operating lever is positioned so that it holds the gate closed even unpowered.

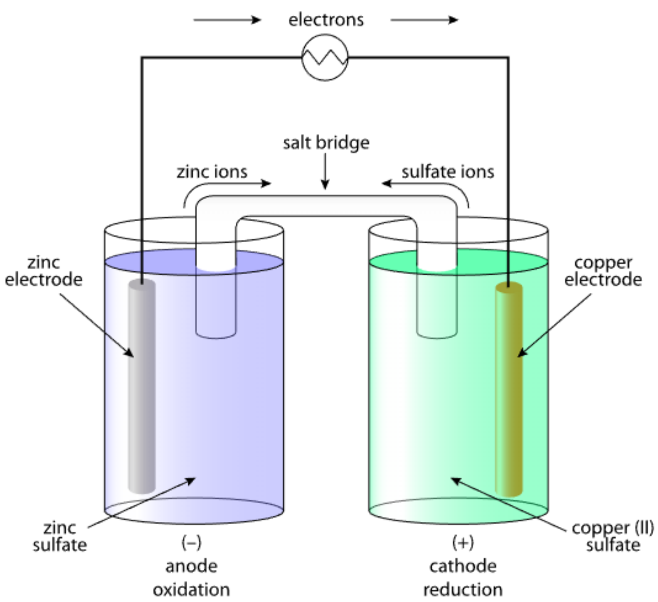
In order to guarantee the batteries to be ready for operation always, the system needs to have a battery specific charging circuitry, which handles the charging and keeps the voltage levels at the right place for the chosen battery type.

The required capacity for electric charge in the battery system was determined in the testing section, where the current consumption of the servo motor was measured under varying circumstances.

4.8.1 Cell chemistry

The demanding operating environment sets also strict demands for the used cell chemistry. The terms battery and battery pack are used to describe a system which consists of multiple battery cells (not excluding single cell systems, for example, standard AA alkaline battery). The cell is a basic electrochemical unit that contains the electrodes, separator and electrolyte [7]. The chemistry of the cell defines its voltage output, current generation and other properties. The word chemistry is used to describe the used active materials as the anode (negative electrode) and as the cathode (positive electrode).

Basic electrochemical energy cell consists of an anode, a cathode, an electrolyte and the separator. The anode (negative electrode) releases electrons to the external circuit and is oxidised during the electrochemical reaction. The cathode (positive electrode) accepts the electrons from the external circuit and is reduced during the discharge (electrochemical reaction). The electrolyte provides the medium for transfer of charge as ions inside the cell between the negative and positive. The separator is there to electrically isolate the electrodes. Picture 4 demonstrates the working principle of Daniell Cell, which was invented in 1836, by a scientist named John Frederic Daniell. The same working principle applies to all energy cells using redox reaction. [7]



Picture 4: Daniell Cell [https://en.wikipedia.org/wiki/Daniell_cell]

The Daniell cell uses zinc as an anode and copper as a cathode. The suitability for materials to act as an anode or a cathode is determined by their ability to act as an oxidizing or reducing agent. Good reducing agents have low electrode potential (surplus of electrons), and good oxidizing agents have high electrode potential (deficit of electrons).

The ideal battery type for this application should have long-lifetime, low self-discharge rate, high enough current output capacity and temperature tolerance.

Generally, electrochemical batteries are divided into primary and secondary batteries. Primary batteries are fully charged on assembly and the electrochemical reaction cannot be reversed (no recharging, one-time use, i.e. alkaline cell batteries). The strength of primary batteries lies on their very long shelf life, and low self-discharge rate.

Self-discharge is a process, where the electrochemical reaction (discharging) happens internally on its own. Different chemistries have different rates of self-discharging, which is crucial information for our application, where the battery is possibly in “storage” mode for a long period of time. [8,9]

The largest difference between primary and secondary battery cells is the ability to recharge the secondary batteries. Most commonly available commercial chemistries for secondary type cells are Li-Ion, Li-Mn, LiFePO4, Nickel Cadmium, NiMH, SLA (lead acid) and Silver oxide. All these types have their own characteristics and slight differences in performance. Table 1 and Table 2 provides information on different model’s electrical properties, including operating temperature range.

Table 1: Comparison of energy storage solutions. [10, 11, 12, 13, 14, 15]

Manufacturer	Model	Model description	Type	Nominal Voltage (V)	Nominal Capacity (mAh)	Dimensions (mm)	Charging current (mA)	Discharge rate (A)
Panasonic	N-700AAC	Long life type	NiCd	1.2	700	14.3x50.2	1050	
Panasonic	BK150AAH	Back-up type/ High temperature & long-life type	NIMH	1.2	1450	AA	1450	
Panasonic	UR-18650AA	General Purpose Models	Li-Ion	3.6	2150	18x650	1505	
Panasonic	LC-P067R2	Trickle long life type	SLA	6	7200	151x34x94	1080	21.6
Honcell	IFR32650E	LiFePO4 - Energy Cell	LiFePO4	3.2	6000	32.15x65.00		0.2C / 3C MAX*
Maxwell	BCAP0100	100F Ultracapacitor Cell	Capacitor	2.7	37*	L 46 x D 22		61

These values have been gathered from selected energy storage solution manufacturers data for different models. As manufacturers have different variety of cell types for different chemistries, the chosen models are considered best suitable for the application of this project.

Table 2: Comparison of the temperature ranges of energy storage solutions

Manufac-turer	Model		Discharge Temper-ature range (°C)		Charge Tempera-ture Range (°C)	
			Min	Max	Min	Max
Panasonic	N-700AAC	Long life type	-20	60	0	45
Panasonic	BK150AAH	Back-up type/ High temperature & long-life type	-10	60	-10	60
Panasonic	UR-18650AA	General Purpose Models	-20	60	0	45
Panasonic	LC-P067R2	Trickle long life type				
Honcell	IFR32650E	LiFePO4 - Energy Cell	-20	60	0	45
Maxwell	BCAP0100	100F Ultracapacitor Cell	-40	65	-40	65

4.8.2 Primary vs secondary battery

Technically, the primary battery types could be the optimal choice on paper if the energy capacity is kept high enough. One of the largest down sides for them is the fact that they need to be replaced before they do not have enough electricity to guarantee operationality in situations where fail safe is needed. The primary battery's excellent self-discharge rates would fit a project like this well. The ability to hold charge for longer periods of time does not completely make them superior choice over secondary battery's, as the functionality of the failsafe mechanism needs to be tested periodically. This causes a regular drainage of the battery, generating extra operating cost for the customer. Even though they can stay charged and operational after being disconnected for 10 years (the duration where battery capacity drops below safe threshold due to self-discharging), the testing and maintenance processes could eat up the battery capacity in a lot shorter time. This raises a question concerning the environmental factor that is designing a device with a non-reusable and environmentally high impacting component, a wise choice. The manufacturing process of lithium primary, alkaline and carbon zinc, all may have a non-desirable environmental impact, and the environmental footprint is increased even more by their one-time use nature. The low voltage of alkaline cells would require larger number of cells in series to achieve sufficiently high running voltage for the servo motor. The ability of running multiple charge cycles increases the lifetime expectancy for the batteries significantly. Recharging the batteries enables them to run through their whole life cycle, which in some cases could be up to 300 to 500 charges from full to empty. [16, 17, 18]

4.8.3 Super capacitors

One suggested solution for energy storage was super capacitors. Super capacitors, also known as ultracapacitors, differ from regular capacitor by having much higher energy capacitance. Advantages of using super capacitors instead of conventional electrochemical batteries, are their ability to handle higher discharge and charge currents, which allows them to be fast charged in a matter of minutes or even seconds. Another advantage is their significantly higher cycle count and wider operating temperature range. For example, BCAP0100 2.7V 100F ultracapacitor cell by Maxwell Technologies, data sheet sets the standard operating temperature range from -40 °C to 65 °C at 2.7V (and extended range from -40 °C to +85 °C at 2.3V), and projects 500 000 cycles at room temperature. The datasheet also projects lifetime of 10 years at rated 2.7 volts at 25 °C. During the study of the super capacitor option, the conclusion about their suitability for the product studied in this thesis project was postponed until more research of the subject is acquired. [19]

5 Product testing

The planned testing for electric shutter targeted four different aspects of the shutter's functions. These aspects were the servo motor's limit testing, reliability of the prototype version 3, controllers' correct functionality (including pressure sensing abilities and fail-safe triggers reliability), effects of dirt accumulation on surfaces and devices capability of operating self-powered on the back-up battery.

5.1 Servo testing

Servo motors testing was planned to focus on determining its operational lifetime by studying the wear down rates, and to ensure the functionality of basic features. The first planned test runs the servomotor from open to closed position under neutral pressures at normal room temperatures. The servo will be let to run its cycle from open to closed with steady pace for so long that it starts to show signs of wear and lowered performance. The number of cycles could be counted by programming a simple counter inside Arduino (if used), or by detecting the actual movement, i.e. by using an infrared proximity sensor to see the closing of the gate and logging the data with time stamps. The advantage of using the sensor approach, is that in addition to the cycle count, also any deviation on the time intervals between the cycles can be recorded. Using only the code-based counter, this could not be possible. The time between cycles could be 3 seconds, 1.5 seconds travel time for each direction. The set interval can be compared to the recorded timing data, to see when any changes to the performance happens. In addition to the speed deviation, another good indicator for wear down could be sound. As the servo's gears wear down, it is possible that they start to make different kind of noise. The sound levels produced by the servo could be recorded using appropriate metering device, to compare the data for any changes over time. Third possible way of detecting wear down, could be to monitor and log the current used by the motor. For example, wearing down or dirt caused by it could make the gears to stop moving rotating smoothly, causing extra work for the motor, which could cause increased current consumption.

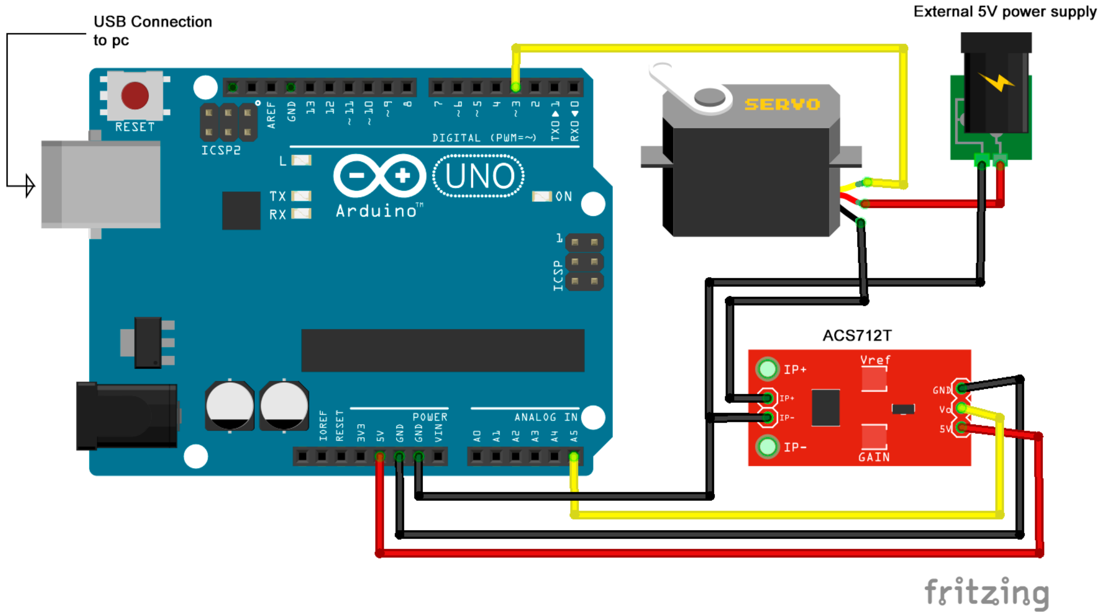
The previously introduced idea of monitoring the current, counting the movement and recording the sound could be used for other tests, where the servo motor is running in different environments, or at different speeds. The effect of high and low temperatures on the servo's performance should be studied thoroughly. Test temperatures should be at least the guaranteed operating temperatures for the device, preferably certain amount higher/lower (e.g. high temperature test at 65 °C and low temperature test at -45°C)

Another important environmental factor affecting the servo, is the pushing force caused by the air pressure. Using the previous knowledge, the measuring should be done when the servo is operating under load. The load could be simulated by using properly sized weights hanging on the servo's arm, or with more complex approach, by testing the shutter in its real environment, with air blown inside the device. Using the appropriate air flow monitoring equipment, the force caused by it on the shutters motor could be calculated in theory.

5.1.1 Current consumption metering

One of the test areas was to study the servo motors current consumption in different scenarios. The results for this test were required to determine the needed energy capacity for the back-up power system. As the chosen type of servo motor was not available during this experiment, a similar sized servo was used to get a rough approximation on what to expect for the electricity consumption.

Current consumption data was measured from the servo using a self-constructed Arduino based current meter. The metering system uses an ACS712T 20A current sensor. The ACS712T is a Hall-Effect-Based linear AC/DC current sensor. It is capable of measuring currents up to 20 amperes, and the manufacturer promises total output error percentage of 1.5 at T = 25 °C [20]. The layout of the meter is rather straight forward, the sensor is connected to Arduinos +5V, ground and Analog pin 5, and in between the ground wire coming from the motor.



Picture 5: Physical design of the currenta meter. Picture made with Fritzing.

Arduino was programmed to run two different kinds of servo movement tests. The first test rotated the servo motor free of load continuously back and forth its full rotation angle (approximately 180°), for a duration of 30 seconds.

The second test operated the servo attached to the prototype model, where it continuously opened and closed the shutters gate, simulating an accelerated real-life scenario. Compared to the first test, the angle of rotation is smaller in this experiment, but the servo may need to work harder as it pushes the gate closed. The effect of higher load to the current consumption is the focus target on this test.

To make the results a little more reliable and to have more data, both tests were repeated 5 times, to get a total measurement time of 150 seconds per test. The Arduino was programmed to serial print the sensors current readings and the time stamps to Arduino IDE’s serial monitor with 10ms intervals. The values were then copied to Excel, where the data was analysed and visualized. The results from this experiment are presented in the final chapter.

5.2 Testing the controller unit

The controller's normal operational actions should also be tested. The test should focus on how accurately the system recognizes the air flow changes, power outages, and how well it responds to them, by closing the shutters gate, or by changing to the back-up power. These situations could be easily simulated by constructing a test setup, where an air blower unit is generating airflow to different directions. The electricity outage detection testing can be completed with observation and power supply unit with the ability to be turned on and off.

5.3 Testing magnetic surfaces

As explained in chapter 4.6, the use of magnets in the design requires thorough testing in different scenarios. Testing this section consists of basic testing of the solution under normal operational situations, and due to the completely new way of handling the gate, testing more specific scenarios is required. More in depth version of this chapter can be found in Appendix 1.

6 Final version and discussion

The aim of this chapter is to present the selected prototype of the shutter, and to explain the reasons for its different aspects. Commercial version of the shutter was not the goal on this project.

The selected version of the electric shutter for this thesis is presented in the following chapter. This final chapter also discuss and presents the design ideas that could be implemented in the future, and which are needed to reach the commercial version.

6.1 Proposals for the next steps

In the current state the first production revision is ready to be manufactured using correct materials. The next step would be to order a small set of machined parts, which should be used to ensure the proper functionality of the device. Ordering a small batch of machined parts, could be expensive, and currently it may seem to be difficult to find a metal workshop that even takes in small orders at a reasonable price. The 3D printed prototype parts are good for testing out how well the parts fit together, and how the overall functionality works, but the plastic parts are not suited for testing the sealing ability of the shutters gate, due to the layered technique that the printer uses to create objects, which can be observed as small grooves around the object. The grooves can be sand down by hand, but the work required to achieve a metal like smooth and accurate surface would be too high. And even if the sanding down of the plastic was done successfully, the sealing ability would be dependent on the quality of the hand work, and thus could not be used to further develop the shutter.

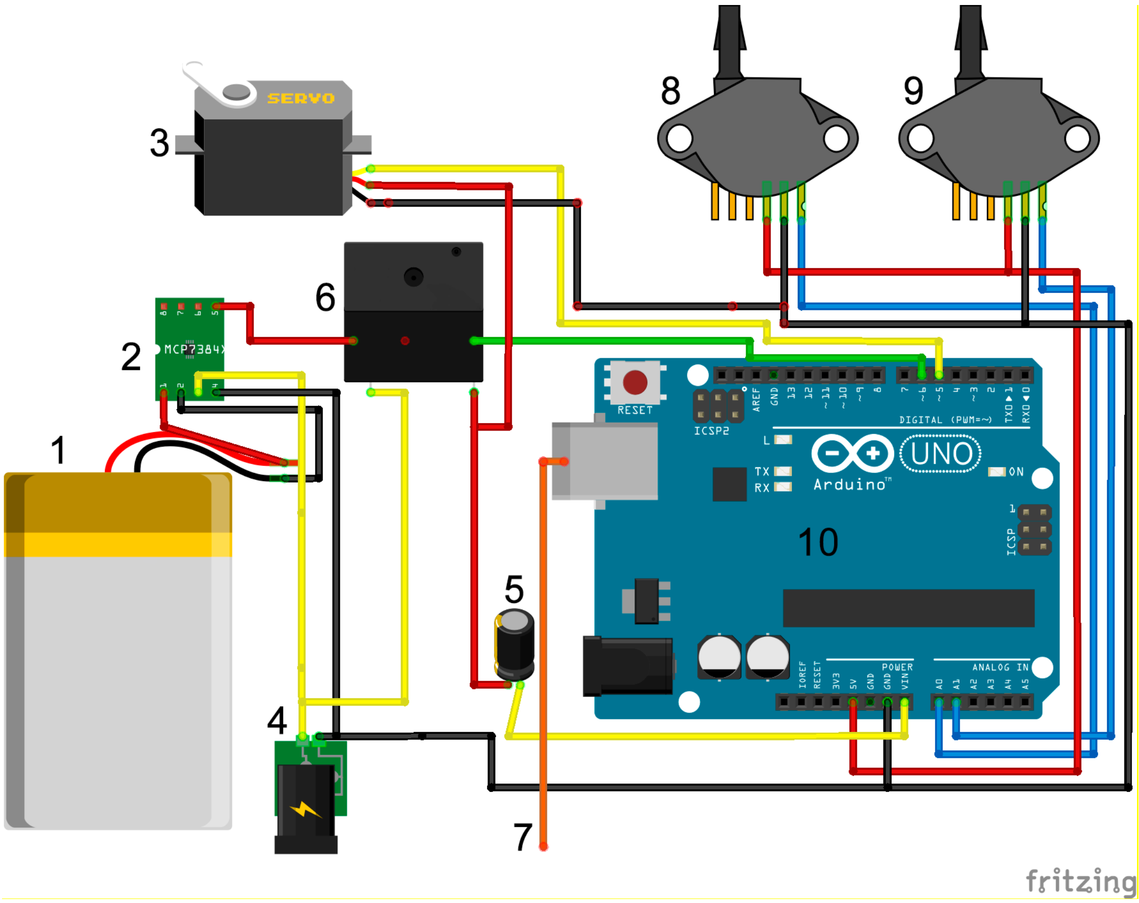
6.2 Electronic control and the backup system

At this moment, the design for the electronics are solely on paper. The battery types suitable for the back-up system was studied previously on the Design Process chapter. As the battery cell alone is not enough, the control and charging circuitry need to be designed in the future. That design process would require a decision on how the circuitry is built from the ground up. The circuitry could be designed all in house, meaning ordering all the components individually, designing and ordering the printed circuit boards and assembling/soldering them by hand. Alternatively, a cheaper and quicker solution would be to use premade circuits. The charging of the selected type of energy storage method requires a charging circuit designed specifically for it, as the different battery chemistries and capacitors require different charging voltages and currents. Charging could be handled by using power management system PMC/PMS circuits, which charges the cells with appropriate currents and voltages. The controlling of the backup system could be easily managed by Arduino microcontroller. Although the initial use for Arduino is for prototyping, there is no major reasons for not to use it in the final product. They are widely available, relatively cheap and easy to use and the PCB can be made in a way which enables plug and play installation. The Arduino can complete all the tasks that is required from the electric shutter. It can control the servo motor, read signals from different sensors, such as the air pressure sensors, manage and control the back-up system, and trigger the fail-safe function on demand.

The main tasks for the microcontroller would be to control the shutters gate and to trigger the fail-safe function when one of two conditions are met: when the external power supply is down, and/or when the instrument/blower air is offline. If the client is using blower units manufactured by Company Oy, they could be configured to send status signal (high/low) to the monitor unit, from where it could be transferred to the electric shutters micro-controller as simple high/low signal and read by AnalogRead command inside the controller.

The way of sensing for the insulation air malfunction/no air input should be done at least by measuring the air difference between the stack side and inside the device. One of the possible ways to measure the pressure is to install a simple pressure sensor into the threads leading from inside the product to the shutter chambers air via 5 small holes, as explained during the design process chapter. In order to determine the air flow direction, another pressure sensor should be installed inside the transmitter enclosure, to have a reference pressure from the “cold” side of the shutter. The two readings are analysed and compared inside the Arduino, and by set parameters the controller figures out if the airflow direction is correct, and if not, triggers the fail-safe.

The fail-safe sequence is responsible for activating the back-up power system, where the used power source is switched to the internal energy system, in the absence of external power supply. In order to complete this task, the controller needs an input indicator for the state of the power supply. This could be done by running the external supply current through a step-down converter into one of the analogue ports. As the Arduino can take in 0 to 5 volts, the step-down converter should limit the incoming voltage to a maximum of 5 volts. The logic behind the analogue input would be to monitor the input voltage. If the input voltage is at steady 5 volts, the device stays connected to the external power, but if the input voltage drops below certain threshold, i.e. below 3 volts, it indicates that the external power connection is unstable, and the controller triggers the failsafe function and starts powering the shutter from the backup battery. The power routing change could be done by using relays. Arduino can handle the relays by connecting them to digital output pins, which can be coded to high or low state when certain condition is met. In the design made during this thesis project the fail-safe trigger opens the relay controlling the external current flow and closes the connection from the battery system.



Picture 6:Suggested starting point for the development of the control system.

Picture 6 visualizes the suggested starting point for the future development of the electric shutters control system. The components shown are not accurate, and they are only used as visualization. Explanation of the numbers: 1) back-up energy storage, 2) charging circuitry for the back-up energy storage, 3) servo motor, 4) input power, 5) a method to keep the microcontroller powered up after detecting power outage and to change to back-up power, 6) a method for changing the used power source, 7) outside communication for remote control and monitoring, 8) pressure sensor 1, 9) pressure sensor 2, 10) microcontroller unit.

6.2.1 Servo current consumption test

In order to determine the needed energy storing capacity, the current draw from the servo unit was measured in the testing chapter. Test results for the first test, where the servo made a sweeping motion on its full rotation angle without any load, showed an average current consumption of 0.626A during the full test period. Maximum current measured peaked at 2.44A, and the average of 20 highest values was 2.03A. The graph in Figure 1 is constructed of 2355 different data points collected from the serial monitor.

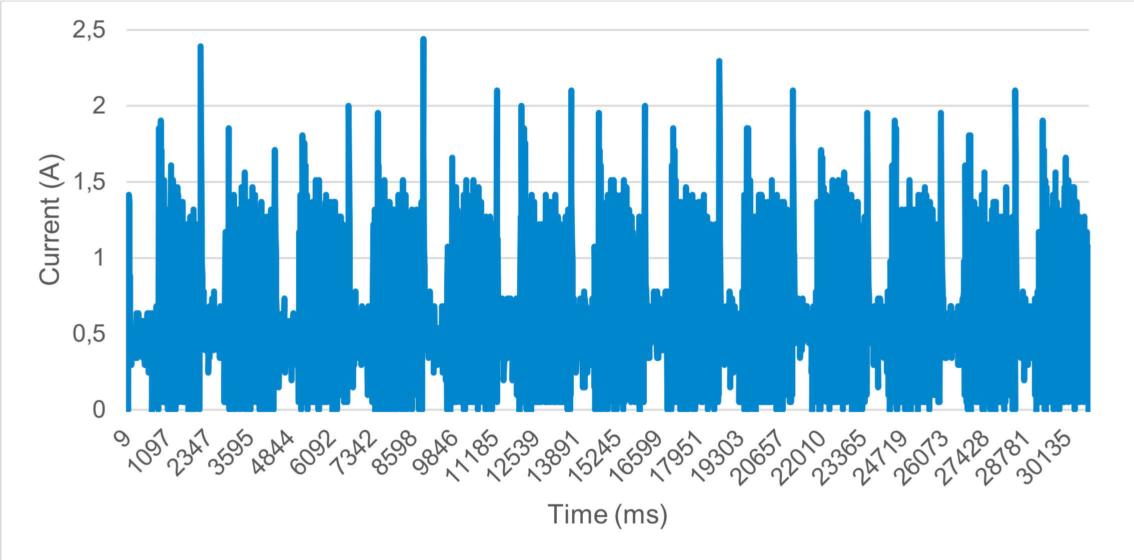


Figure 1: Current measurements for Test 1.

To make the graph easier to interpret and to see the fluctuations more clearly, a rolling average of 4 values were used to create the graph in Figure 2.

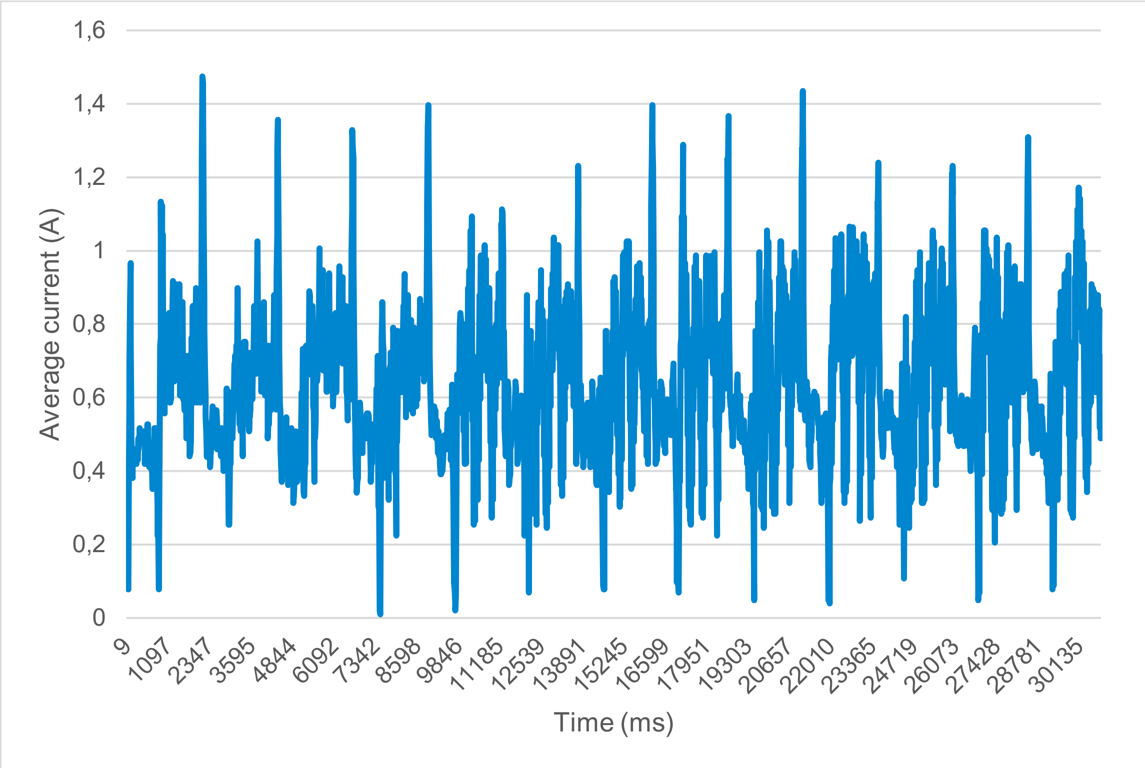


Figure 2: Rolling average of the measurement data for Test 1

These figures could indicate that the current draw peaks at the point, where the motor is changing direction, and the average current during the movement stays around 0.4 to 0.8 amperes.

The second test procedure differed from the first one so that the servo made only the motion to open and close the shutters gate, where the full rotation cycle is not needed. The measurement was done so that the shutter was closing and opening the prototype versions gate. The closing cycle was programmed in a way that caused the servo to push the gate firmly closed, and this was expected to cause higher current draw peak.

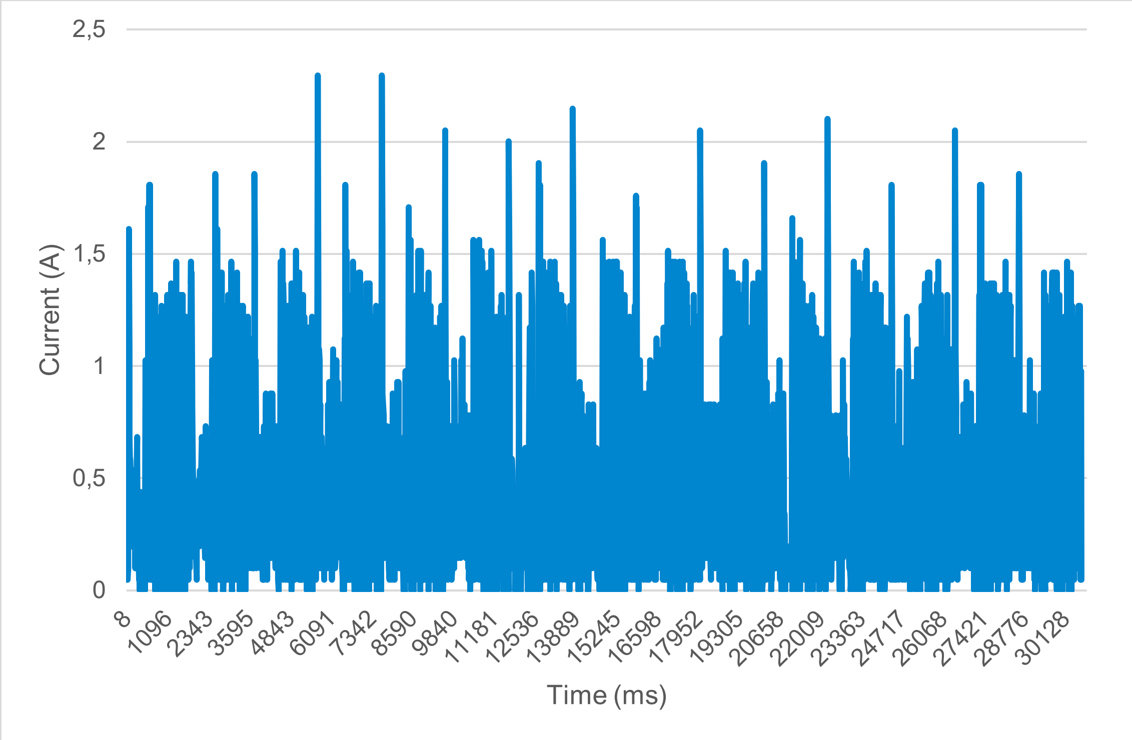


Figure 3: Current measurements for Test 2.

The test results showed that it was not the case, and in fact the average current consumption was lower than in previous test. The average of all the 2342 measurements was 0.519A, maximum peak value was 2.295A, and the average of 20 peak values were 1.950A. Figure 4 presents the rolling average of the data points.

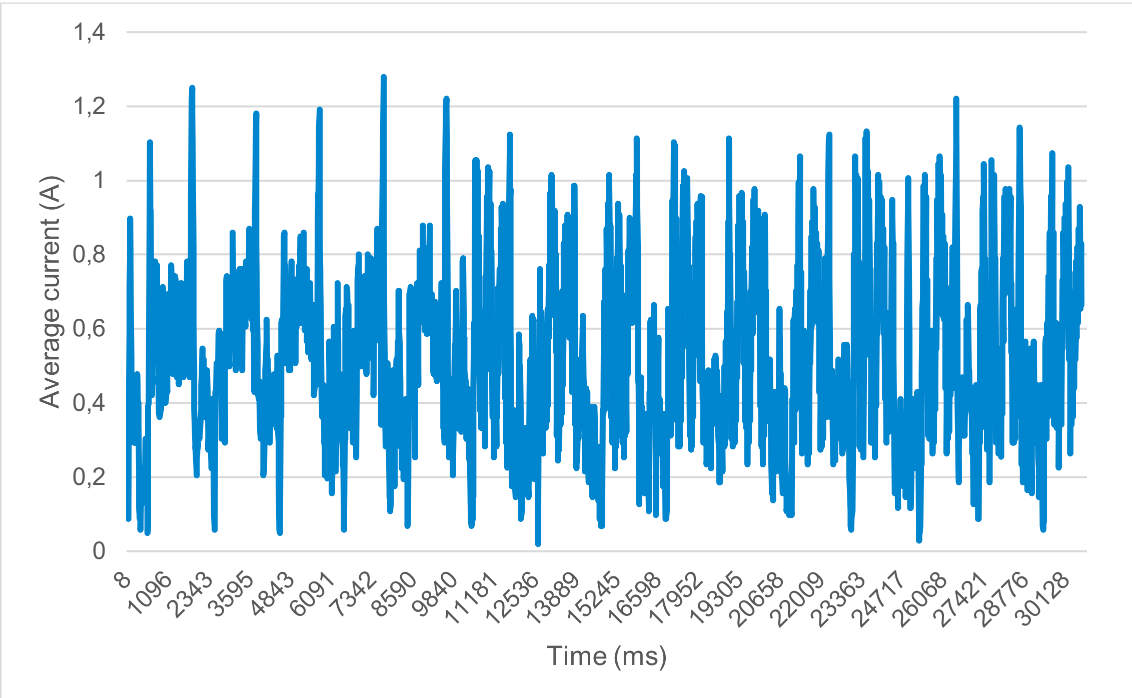


Figure 4: Rolling average of the measurement results for Test 2

According to the second measurements rolling average graph, the shutter made more direction changes during the 30 second measurement period, but the overall average stayed lower than previously. The expected current peak caused by the forceful closing of the gate, did not appear in the measurement data. The reasons causing this requires more studies. The lower overall average current could be caused by the smaller movement range. Even though the current draw peaks at direction changes, the current draw during the travelling could influence the average value more, and thus the lower result in the second experiment.

It should be also noted that as the current meter setup was constructed just for this project, it was not calibrated properly.

6.2.2 Energy storage capacity

The data from previous section allows us to approximate the needed energy capacity for the back-up power system. The average value from current measurement test 1, was 0.625A. As the data was collected only for 30 x 5 seconds, it can be approximately assumed to be relatively same for a duration of 1 hour of continuous sweeping. One hour of 0.625A means that the current consumption is around 0.6Ah. The idea behind the backup power system was that the shutter can operate on its own, even for longer periods of time. The chosen time was set to be a minimum of 1 hour. In addition to the power required by the servo, also the Arduino requires electricity to run. The Arduino board uses Atmel ATMEGA328P microcontroller, which can be assumed to be the most current hungry component. The technical data sheet for ATMEGA328P, lists the current consumption to be typically at 5.2 mA and the maximum at 9 mA. [22] Adding all the other components of the Arduino together, we can approximate its total consumption to be below 100mA. Adding the servos consumption of 0.6Ah and the 0.1Ah from other components, it totals in 0.7 Ah energy consumption. In order to minimize the effect of calculation or approximation errors, a capacity of 1 Ah should be enough to guarantee one hour of active operation. As the current consumption from the servo is much lower during idle, the 1000 mAh capacity could be slightly oversized, which should not be a problem on this scale.

6.3 Material selection

The range from where the material was chosen, was restricted to the most common industrial production materials, which are; carbon steel, stainless steel and aluminium. They all are widely used materials; therefore, they are also widely available. Aluminium and steel are relatively cheap as materials, and cheap to manufacture/machine, compared to stainless steel, as the following table on raw material prices indicates.

Table 3: Raw material prices [23,24,25]

Material	Type	Price (€/t)	Date	
Carbon Steel	Rebar	507	December 2018	[23]
	Merchant Bar	555	December 2018	[23]
Stainless steel	Peeled Bar (304)	2350	December 2018	[24]
	Peeled bar (316)	3440	December 2018	[24]
Alumin-ium	Aluminium Alloy	1190	May 2019	[25]

6.3.1 Aluminium

Aluminium is light weight, malleable and highly corrosive resistant metal. It has also extremely good thermal and electrical conductivity. Aluminium metal that is commonly used industrially is almost always alloyed, (alloy=mixture of elements) most commonly with copper, zinc, magnesium, manganese, and silicon. The factors that restricted the selection of aluminium are presented next. Choosing aluminium would also have caused problems with galvanic corrosion, as the part where the electric shutter is mounted, is made of AISI 304 stainless steel.

Galvanic corrosion happens when metal is in contact with another conducting material in a corrosive medium. When the two metals are exposed to an electrolyte, a galvanic current flow from one to the other. Most commonly, the galvanic corrosion causes faster deterioration of metals, but it can also be beneficial in some cases, as it is used to achieve corrosion protection for the attached metal.

In our case stainless steel would be in contact with aluminium and air humidity could be acting as the corrosive medium [26]. The accelerated rate of deterioration of the metals are not desired property for the product.

In addition to previously stated facts, one of the largest reasons for disqualifying aluminium was its thermal properties. Aluminium has a melting point at 660°C [27], which is too low for the requirements set by the targeted installation environment. Due to these facts, Aluminium was not chosen to be the product material.

6.3.2 Carbon steel

The basic grade of industrial steel is relatively cheap, strong solution for production material. In comparison to stainless steel, the non stainless version is much less difficult to machine, which makes it even cheaper. The drawbacks for steel are its ability to withstand corrosion and chemicals, and since steel is ferrous metal, it is magnetic, which causes problems with our magnetic connection link design. The poor corrosion and chemical resistance were the largest reasons for disqualifying carbon steel. [28]

6.3.3 Stainless steel

The final production material for the mechanical parts of the shutter was chosen to be AISI 316 grade stainless steel. The reasons for choosing AISI 316 stainless steel, for production material is that stainless steel is strong and durable. It can withstand corrosive chemicals, tolerates high temperatures without losing too much room temperature toughness (can be used at temperatures up to 1093 ºC), and it is non- magnetic, which allows the magnetic link to function in a proper way (and allowed us to even consider that as an solution in the first place). [29]

The AISI 316 differs from the more common AISI 304, by having slightly higher nickel content and 2-3% molybdenum, which gives it better chemical and corrosion resistance. Type 316 was developed to resist sulfuric acid compounds in sulphite pulp mills, but its use has been broadened to other process industries. [30]

Different grades of stainless steel

There are available over 100 different types of stainless steel. AISI 304 is the most commonly used grade of stainless steel. Table 4 shows that the differences on mechanical properties between our selected steel types are not that significant. The largest difference can be seen in the elongation percent in 2”, which is 5 units lower in type 316.

Table 4:Chemical analysis and nominal mechanical properties of different types of stainless steel. [31]

Chemical Analysis % (Max)									Nominal Mechanical Properties					
									Tensile Strenght		Yield Strenght		Elong. in 2"	Hard-ness (rock-well)
Type	C	Mn	P	S	Si	Cr	Ni	Mo	ksi	Mpa	ksi	Mpa	%	
304	0.08	2	0.045	0.03	1	18/20	8/10		84	579	42	290	55	B80
304L	0.03	2	0.045	0.03	1	18/20	8/10		81	558	39	269	55	B79
316	0.08	2	0.045	0.03	1	16/18	10/14	2/3	84	579	42	290	50	B79
316L	0.03	2	0.045	0.03	1	16/18	10/14	2/3	81	558	42	290	50	B79

Machining stainless steels is more difficult compared to other alloys, as it being tough, gummy and has tendency to seize and gall. This maybe reflected on increase in the machining costs. As stated previously on this thesis, the shape of the parts is designed to ease the machining process as much as possible, to keep the manufacturing costs lower.
[32]

Type 316 belongs to a subgroup of stainless steels called austenitic stainless steels [35]. Austenitic steels contain 16 to 26 percent chromium, and up to 35 percent nickel. Our selected grade 316, has 18% chromium and 10 percent nickel.

Austenitic steels are considered non-magnetic, due to their low magnetic permeability. In order to be fully non-magnetic, the material should have magnetic permeability of 1. The austenitic stainless steels have magnetic permeability in the range of 1.003 to 1.05, which is low enough to allow its use in applications where non-magnetism is required. The slightly over 1 value is a result from the few percent content of delta ferrite, which is maintained to make the material more readily weldable. The permeability of any steel is dependent on the distribution of ferrite, martensite and austenite in the structure. Austenitic steels retain their austenite structure in room temperatures, which results in the low magnetic permeability. [33] Austenitic steels can become slightly more magnetic by cold working, but in our case where cold working is not used, this does not affect our decision. [34, 35]

The materials for fasteners should be chosen considering all the previously studied factors. Therefore, most desirable material for bolts and washers should match the production material, which is stainless steel. Due to the small size and complexity of the arm controlling the movement of the shutters gate, it might be too difficult to manufacture it out of stainless steel. Due to time limitations this could not be tested properly in time during this thesis. One possible solution for it could be to 3D print it with high performance printing material, such as PEEK. As an example, one manufacturer PEEK filament properties include good mechanical strength, excellent chemical resistance and continuous use temperature of 260°C. See Table 5 below for more specific mechanical properties.

Table 5: Mechanical properties of peek filament. [36]

Mechanical Properties	Standard	Unit	Metric
Tensile Strenght	ISO 527	MPa	100
Tensile Modulus	ISO 527	MPa	3720
Tensile Elongation	ISO 527	%	28
Flecural Strenght	ISO 178	MPa	130
Flecural Modulus	ISO 178	MPa	2700

As the use of PEEK as material is merely a suggestion at this point, the suitability for it needs more research and testing in person. The use of 3D printer allows for more complex shapes in the design, but the heat tolerance capabilities, such as ability to hold strength in higher temperatures, of the polymer may prevent its use. The arm will have a magnetic rod with stainless steel spring. The same kind of magnetic rod is also used inside the gate.

6.4 Maintenance schedule/guideline

This sub chapter covers the recommended maintenance and repair timelines for the designed customer version of the electronic shutter. As the shutters design could be changed in the future, also these recommendations are subject to change.

6.4.1 Servo Motor

The desired lifetime for the servo motor is 5 years. The servo motor should be able to handle at least that time period of normal use. Normal use means that the servo is in idle state for most of the time, and only moves the shutter occasionally. In our application, the actual active time for servo, where it moves the motor, stays relatively low, as the servo is only operating actively when the shutter is opening and closing, the passive stage of operation does not wear down the servo, because the servo arm should stay on its own position without stressing it too much, even unpowered. Replacement for the servo is suggested at minimum once in 5 years, or more frequently in demanding environments, or if any unnecessary noise or movement from the motor is detected.

6.4.2 Battery pack / Backup Power

Due to the nature of current battery technologies, in order to guarantee optimum operation for the fail-safe function, the condition of the back-up battery should be monitored frequently and replaced every 5 years. The fail-safe function needs to be tested periodically, and maintenance if needed.

6.4.3 Cleaning

To keep the equipment operating on the most optimal performance level, the shutter gates chambers, and the shutters gates, surfaces should be kept clean. The airflow design for the interior compartments utilizes the airstream as a cleaning agent, so the manual cleaning is required less frequently. The suggested cleaning interval needs to be determined based on the nature of the installation environment.

6.5 Discussion

The goal for this project was to design an electrical version of the existing shutter unit. Three different prototyping version were developed and tested, the latest version of them was chosen to be developed further. The main project goal was achieved with this chosen version of the product.

The most important learning outcome from this thesis, was the importance of time management. Even though, the goal was achieved, it could have been achieved in shorter timespan with better time management. Setting smaller development goals on the fly, and deadlines for them, could have made the process quicker and more efficient. In addition to higher number of smaller milestones, these could also have been accompanied with more frequent meetings with the lead design manager at the Company Oy.

The selected prototype unit is ready for the next phases of testing and fine tuning by the Company Oy, which will continue the work on their behalf to accomplish the commercial version.

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Appendix 1. Product Functionality