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Industrial Electrical Engineering and Automation

Designing a Cost Effective Encoder for High Performance Doors

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Abstract

The goal of this thesis was to develop a prototype of a cost effective encoder unit for the motors of ASSA ABLOY high speed doors. The encoder will provide feedback for the automatic doors control system and has to do so reliably while being more cost effective than the current solutions used by ASSA ABLOY as well as giving the company more control over the value chain. Multiple encoder technologies are evaluated and tested to find a solution which is most suitable for the high speed doors in question, with the aim to have a functioning prototype compatible with the current control systems and motors.

Starting with a wide scope to explore all possible solutions, concepts for the different sub-problems were generated, prototyped and tested, to then be combined into a final solution. The final developed prototype was built and is presented in this report.

While more testing needs to be done a promising solution narrowed down from a wide variety of concepts and technologies for the encoder has been developed and prototyped. The solution proposed is an encoder utilizing optical sensors, providing signals compatible with the current control systems and motors without modification. In addition to this it would provide value for the company, not only in terms of being more cost effective than current solutions, but also giving more control over the value chain.

Keywords: Encoder, High speed doors, Motor, Product development, Prototyping, ASSA ABLOY

Sammanfattning

Målet med detta arbete var att utveckla en prototyp av en kostnadseffektiv pulsgivare till motorerna för ASSA ABLOYs snabbrullduksportar. Pulsgivaren ger återkoppling till de automatiska dörrarnas kontrollsystem och ska göra detta på ett tillförlitligt sätt samtidigt som de ska vara mer kostnadseffektiva än de nuvarande lösningarna som används på ASSA ABLOY. Utöver detta ger en egen produkt företaget mer kontroll över försörjningskedjan. Flertalet olika typer av pulsgivare har utvärderats och testats för att hitta en optimal lösning för snabbrullduksportarna i fråga, med målet att bygga en fungerande prototyp kompatibel med de nuvarande kontrollsystemen och motorerna.

Med ett, till en början brett, omfång för att utforska alla möjliga lösningar genererades koncept för de olika underproblemen i produkten. Prototyper på dessa lösningar togs fram och testades för att sedan kombineras till en slutgiltig lösning. Den slutliga prototypen byggdes och presenteras i denna rapport.

Även om det krävs mer testning så har en lovande lösning, framtagen från en stor mängd av koncept och teknologier, designats och testats. Den föreslagna lösningen använder optiska sensorer för och överför signaler som är kompatibla med de nuvarande kontrollsystemen och motorerna utan behov av förändring på dessa system. Utöver detta ger den värde till företaget, både i form av att den är mer kostnadseffektiv än nuvarande lösningar och genom att ge bättre kontroll över hela försörjningskedjan.

Nyckelord: Pulsgivare, snabbrullduksportar, Motor, Produktutveckling, Prototyp, ASSA ABLOY

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Lund, May 2023

David Petersson & Emanuel Edelstam

Contents

List of abbreviations

Abbreviation	Definition
CAD	Computer aided drawing
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
IK	Impact protection
IP	Ingress protection
LED	Light emmiting diode
LTH	Lunds tekniska högskola
PCB	Printed circuit board

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Introduction

In this chapter the project is introduced, with goals, limitations and the system on which the project is aimed at. There is also information on how to read, and more easily navigate the report.

1.1 Background

ASSA ABLOY Entrance Systems IDDS AB is an international company with a site in Landskrona that develop and deliver a range of different solutions for doors, entrances and gates for people and vehicles. Most of the systems are complex with many parts where software often has to be combined with hardware to produce safe and reliable products. One of these product lines are roll up high speed doors (1.1). These doors are automatically opened and closed using proximity sensors when a person or vehicle is moving towards the door, and are often used in industrial environments. The characteristics for these systems include a quick opening or closing movement allowing for smooth flow of people or vehicles and a good insulation between the sides to keep the climates separate. To open the doors automatically in a safe and durable fashion, a key component of the control system is feedback from the door on how fast and what direction the door is moving. The motor speed can be used to derive the speed at which the door is moving up and down with a higher precision than measuring the output shaft from which the door is being rolled which is the current solution. By instead attaching an encoder to the motor shaft, signals can be sent to the control system giving the needed feedback to control the door position and speed. ASSA ABLOY now want a low cost solution that can be assembled in house and attach to any of the motors for their high speed doors.

1.2 Goal

The goal of the project was to evaluate possible solutions for an external encoder compatible with the motors of ASSA ABLOYs high speed doors. This entails deciding what encoder technology to use as well as developing a complete solution and prototype that is compatible with and can be used with the current control system at ASSA ABLOY. Through testing and evaluating different solutions a final product should be prototyped and the working process is presented in this paper. Factors that have been evaluated are compatibility with the current system, environment resistance, ease of use and ease of production and assembly.

1.3 Delimitations

In order to have a clear scope and final goal, a number of limitations were set up:

- The encoder should provide measurements through signals that are compatible with the current control systems for high speed doors at ASSA ABLOY but does not need to be compatible with the other systems at ASSA

- The encoder should be its own unit that attaches to the current motor, i.e. no changes to the current system should be done

- The encoder should cost less than the currently used solution as well as applicable solutions available on the market, but no exact final price needs to be established

- A working prototype should be built, but no investigation of the manufacturing process is done other than the product being manufacturable

1.4 Current system

The systems that apply to this project are, as mentioned above, high-speed doors. These systems consist of a set of main parts: a motor, a roll-up vinyl door, a 7:1 worm wheel gearbox, a shaft onto which the vinyl door gets rolled up, a control unit, a shaft detection unit, a Dynaco DNC2+ encoder and proximity sensors. The control unit controls the system and supplies the different parts with power. It also receives the signals from the sensors as input to send the correct signals to the system, automating the door. With the current system two pulse-trains with a half a period phase shift are produced by the encoder which gives information on the direction and speed of rotation in the motor and roll-up shaft. The shaft detection unit is a safety-precaution which detects if the crank for manual turning of the motor is inserted into the motor hole. It works by having a simple mechanical switch which sends a signal to the control unit when something pushes on it, stopping the motor from running at the same time. In Figure 1.1 the current system setup can be seen with the specific parts marked out.

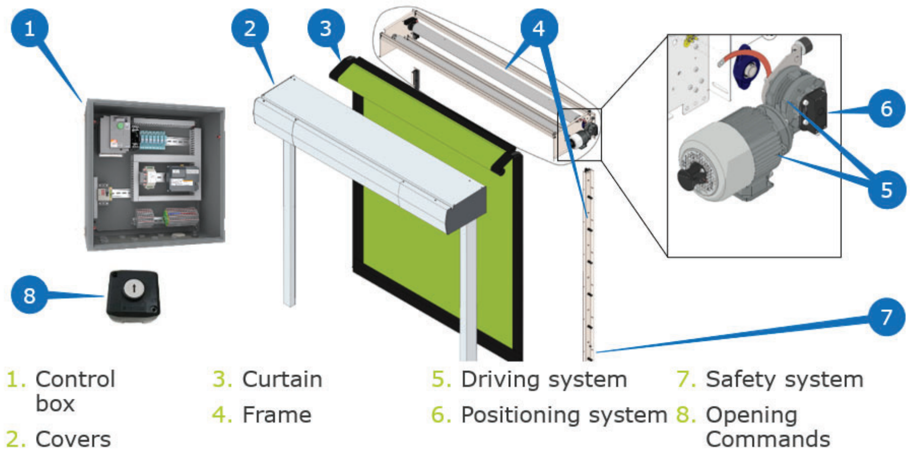


Figure 1.1 Overview of high speed door system [Pede, 2021]

1.5 For the reader

In this report the whole design process for designing the encoder is presented. There are parts of the process that were not used for the final product and could be considered redundant for the development of the final encoder. These will still be included in the appendix B.1 and is referenced in relevant parts of the report, to transparently show the full design and prototyping process. If the reader is only interested in the parts of the process that were actually used for the final product this section can be skipped.

2

Theory

In this chapter the theoretical background and basis of the project is presented. Different types of encoder technologies as well as the control system used at ASSA ABLOY, to which the encoder is connected to, is evaluated.

2.1 Encoders

There are many types of encoders with different functionalities and purposes that are being used today. Depending on what they are to be used for they are constructed in various ways and produce completely different signals, but the simplified explanation is that they provide a way to measure physical properties and produce readable electrical signals, in order to get a digital interpretation of physical values. This is used in all kinds of areas, from industries to consumer products that we use on a daily basis.[Anaheim Automation, 2023]

2.2 Encoder type in this project

In this project the speed and direction of the motor on ASSA ABLOY high speed doors will be measured. Since the encoder is going to measure rotation there are two main types of encoders which could prove useful; incremental and absolute rotary encoders. The major difference between these encoder types is that the absolute encoder always keeps track of the exact angular position of the encoder, while the incremental encoder only measures the speed and direction of rotation. Both types could prove useful for this project, however, since the currently used solution is an incremental encoder, that is what the control system is compatible with. While using an absolute encoder would give the positional data directly, this is already handled in other ways by the current control system. Changing from incremental to absolute encoders could require alterations to the control system without actually giving any improvements to the systems capabilities, which is not desirable. Because of this and the fact that positional data from the encoder is unnecessary, the decision was made to only include incremental encoder solutions in the product development and project.[Smoot, 2018]

2.3 Incremental encoder technologies

There are multiple technologies that can be used to achieve the incremental encoder functionality, with the most common ones being; optical encoders, magnetic encoders, capacitive encoders, mechanical encoders and resistive encoders. Every technique has different characteristics that make them suitable for specific applications. In this project they have all been evaluated in the product development process to find the optimal technique for this specific application.[Kovacheva and Yakimov, 2013] [Incze et al., 2009]

2.3.1 Magnetic encoders

Magnetic sensors work by detecting the presence, strength or direction of a magnetic field, which in encoder applications can be generated either from a permanent magnet, or an electromagnet. These fields can be measured without physical contact making them ideal for motion sensing. A magnetic field is a vector quantity with both magnitude and direction that can be measured in various ways by magnetic sensors [Muñoz et al., 2005].
One of the most common magnetic sensors is the Hall effect sensor. It measures the strength of the magnetic field compared to magneto-resistive sensors which measure the direction of the field. While measuring the direction rather than the strength of the field gives a few advantages, the affordability and precision of hall effect sensors make them a popular choice for magnetic sensors.
Hall effect sensors contain a Hall effect element that, when exposed to a magnetic field outputs a voltage proportional to the strength of the field. The output voltage is very small and needs to be amplified to be of use in electronics and the elements are usually combined on an integrated circuit to create a basic Hall effect sensor. A benefit of Hall effect sensors is that they have a wide temperature range -40 - +150C° which means they can handle many industrial environments.
A Magneto-resistive sensor is usually made from a thin film of an alloy that changes resistance when exposed to a magnetic field. This change in resistance can then be used to measure very small changes in a magnetic field. They are around 200 times more sensitive than Hall effect sensors meaning they can have much larger distances between sensor and magnet. The main advantages of magneto-resistive sensors are insensitivity to the temperature coefficient of the magnet being measured, they're more resistant to shock and vibration and they have the ability to handle large differences in the distance between the magnet and sensor. These advantages stem from the fact that magneto-resisitve sensors measure the direction of a magnetic field rather than the strength.

Both Hall effect sensors and magneto-resistive sensors can measure the presence or change of a magnetic field which in turn can be used to measure motion or rotation if there are magnets with changing polarity attached to a shaft or moving object. As the different polarities of magnetic field pass by the sensor the change can be measured and decoded into speed, either rotational or lateral. [Muñoz et al., 2005] Magnetic encoders are very resistant to humid and dirty environments compared to, for example, optical encoders. This combined with the fact that they have a simple and compact structure as well as the possibility to work at high speeds has made them a staple in the automotive industry and many other fields [Miyashita et al., 1987].

2.3.2 Optical encoders

Photoelectric sensors, or optical sensors, react to the presence of all kinds of objects. Optical sensors use a transmitter to produce a light that is detected by a receiver [Muñoz et al., 2005]. When an object blocks this beam of light the output signal from the sensor changes. The transmitter consists of a switching light emitting diode (LED) that generates high energy light pulses. The switching of these pulses, which can be infrared, visible red or green light, provides long scanning distances and penetration in harsh environments as well as a low power consumption. The receiver contains a phototransistor that produces a signal when light falls upon it. Phototransistors are used because they can be tuned to have good spectral match to the LED of the transmitter, has a fast response time and are temperature stable. By tuning the receiver circuit it can be made to only respond to a narrow band around the LED pulsing frequency, thus giving high resistance to ambient light and noise. The use of fiber optic cables allows photoelectric sensors to be used in applications where space is limited as well as hazardous environments. Depending on the sensor the output is either on when light is hitting the receiver, or the output is on when light is blocked from the receiver. Either way the sensor works in very much the same way with the only real difference being the inversion of the output signal. There are different scanning techniques used for photoelectric sensors listed below [Muñoz et al., 2005]:

- Retro-reflective scanning
- Polarized scanning
- Through-scan
- Diffuse scanning
- Fiber optic

Retro-reflective scanning. Retro-reflective scanning has the transmitter and receiver in the same housing with the beam reaching the receiver via a reflector. The advantages of this are the single side mounting, easy alignment and the ability to mount the reflector in small spaces where a separate receiver unit would not fit. The reflector can be either acrylic panels or discs, or reflective tape cut to size. The larger the reflector the longer scanning distances are possible due to more light reaching the receiver.

Polarized scanning. Polarized scanning works very much in the same way as retro-reflective scanning with the addition of a polarized lens. When the light hits the reflector it is turned 90° and can pass through the receiving lens. This prevents false reflections when detecting shiny surfaces.

Through-scan. For a through-scan sensor the transmitter and receiver are separate and positioned opposite to each other so the light from the transmitter shines directly on the receiver. This method gives an excellent reliability, high penetration in contaminated environments and the possibility of long scanning distances. This is the technique used in optical fork sensors.

Diffuse scanning. Diffuse scanning works similarly to retro-reflective scanning with the key difference being that there is no reflector, rather the light from the transmitter is directly reflected from the target to the receiver. This is used in cases where it is impractical to use a reflector or when a specific target should be detected. Because the reflected light is diffused a cleaner environment is necessary and scanning distances are shorter.

Fiber optic. Fiber optic photoelectric sensors can use either trough scan or diffuse scan fiber optic cables. These cables allow for sensing in very space restricted areas and can also detect very small targets. Depending on the application different cable end tips can be used for the solution.

2.3.3 Capacitive encoders

Capacitive encoders utilize capacitance measurements to detect changes to a reference capacitance value. The main parts of such an encoder consist of two metallic stator plates which serve as the capacitor plates and one target in between the plates. By applying an electric charge to the stator plates an electric field is induced between them, with a value depending on the material in between them. The measurement changes occur due to the target, consisting of a dielectric material, moving between the two stator plates which alters their capacitance. By detecting the changes in capacitance the sensor reads that the target is between them, which in combination with having multiple stator plate pairs or stator plate patterns which produce predictable signals, provides information on the dielectric material position or direction of movement. With the dielectric plate connected to a rotating shaft the direction can be directly correlated to the rotation of the shaft. This technology provides some advantages to other technologies in regards to robustness, such as a high resistance to outside electromagnetic interference (EMI) and good performance in dirty environments. Depending on the measurement technique used, they can also be programmed to have different resolutions, by altering the frequency of measurements which in combination with a predictable pattern of signals allows for both a higher and lower resolution. The two most common design choices are having circle sections which detect when something passes between them [Zangl and Bretterklieber, 2004] or having a sinusoidal pattern from which the position can be measured by having predictable signals derived from the given pattern.[YAVSAN et al., 2020] [Yavsan et al., 2021] There are also some drawbacks to capacitive encoders. Due to the nature of capacitances there can easily be disturbances in the measurements if the encoder is not produced with high enough precision. This can occur due to the rest of the circuit also producing a capacitance which is not desirable as it can cause faulty measurements. The signals are usually rather small which also makes disturbances and measurement noise a bigger issue. This is usually handled with filters and amplifiers, which requires careful consideration to circuit design, to not introduce more stray capacitances in the circuit, causing additional measurement errors.

2.3.4 Mechanical encoders

The conductive properties of metals play a big part in electronics and is what is utilized in mechanical encoders. As the movement to be measured occurs, the sensor varies between having a conductive connection and not having one, thus producing a square-wave signal with the current or voltage being measured. This connection can be achieved in multiple ways, for example by using carbon brushes and a pattern of conductive and non-conductive materials to produce the desired output. The carbon brushes would then work as switches, being either open or closed depending on if they are conducting or not.[Elprocus, 2023] Mechanical encoders are quite reliable and robust but could be sensitive to electrical disturbances and dirt if it interrupts the current transmission. Wear and tear could also be a problem, with for instance carbon brushes, since the physical connection would get worn down from continuous use.

2.3.5 Resistive encoders

Resistive position sensors, or potentiometers are devices that when turned increase or decrease the resistance in a circuit. The change in resistance comes from the distance between a fixed terminal and the sliding contact wiper [Muñoz et al., 2005]. As the distance between them increases, so does the total resistance value. Due to the sliding, wiper potentiometers are limited to sensing angles less than 360° unless a vernier drive is added, which slows down the movement of the wiper compared to the turning knob, this does not however remove the maximum measured angle, since the wiper will reach the end of the resistive material after enough turns. With this in mind it makes sense that potentiometers are mostly used as a control where there is a maximum and a minimum value that can be reached. The advantages of potentiometers are that they are low cost, simple theory, both operational and theoretical, they have a built in absolute measurement even trough power-off cycles and they have robust EMI emission and susceptibility performance. A downside of resistive encoders is their sensitivity to wear and tear. With a need for a change in a physical part of the encoder, such as the sliding changing values of a resistor

2.4 Signals and control system

The current system at ASSA ABLOY utilizes a control unit to power the motor and process the signals from the encoder. With the current solution two pulse trains are produced in the encoder and transmitted to the control unit. The sensors for generating the pulse trains are placed with a half period phase shift, which allows for reading both the direction of rotation and the rotational speed. The direction is found by checking which of the two sensors gets blocked first, i.e. which pulse is first. This can be used to derive the rotational direction of the disc. The signals from two optical sensors, A and B can be seen in Figure 2.1.

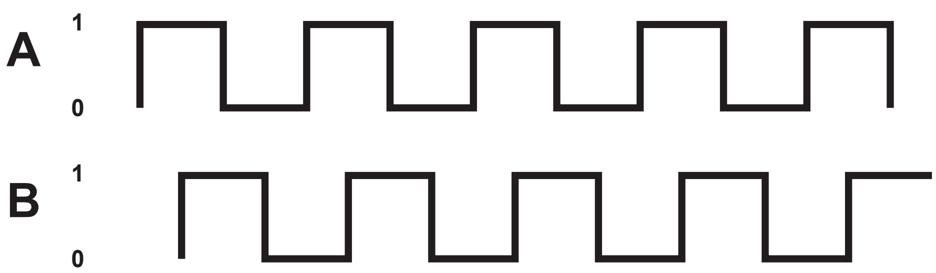


Figure 2.1 The signal output from two optical sensors A & B from rotating a forked disc intermittently blocking them. 1 means the sensor is blocked and 0 means it is not blocked.

These so called pulse trains come from a constant rotation of the slotted disc or forked wheel blocking and unblocking the sensors. When blocked they give a signal of 1 and when unblocked a signal of 0. Through this the rotation can be derived as seen in Figure 2.2.

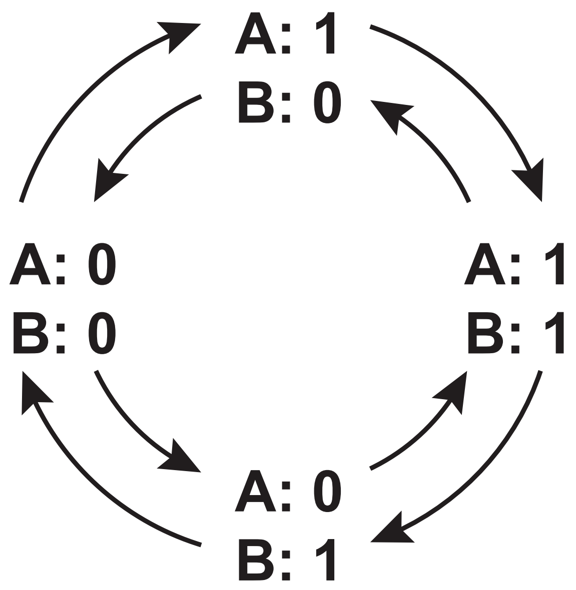


Figure 2.2 The rotation derived from two optical sensors A & B being blocked and unblocked by a forked wheel

It can be seen that this gives a signal fidelity 4 times that of the number of teeth or slits on the encoder disc since one tooth gives a total of four signal changes. The rotational speed is found simply by knowing how many "teeth" the encoder disc has and counting either the pulses in a set time, or measuring how long a pulse shift takes. This leads to the rotational speed being able to be calculated.

3

Methodology

In this chapter different design and product development processes is introduced. The processes described is evaluated in relation to the project and lastly a combined process suitable for the project is introduced. The combined process presented in this chapter has been followed during the work.

3.1 Product development processes

The authors explored different product development processes to find one that was the most suitable for the project. The development processes investigated were Product Design and Development by Ulrich & Eppinger, Human Centered Design Process by IDEO and the Double Diamond Design Model by the British Design Council.

3.2 Ulrich & Eppinger

The Product Design and Development methodology by Ulrich & Eppinger is a model for how the complete cycle from product idea to a finished product is performed. This is done in separate steps which are explained in this chapter.

3.2.1 Product planning

The first step of product development according to Ulrich & Eppinger is planning [Ulrich and Eppinger, 2012]. This stage often precedes the launch and approval of a project. It aims to identify opportunities and it ends in a mission statement with set goals, constraints and assumptions.

3.2.2 Concept development

The next step is the concept development phase. This phase consists of multiple activities; identifying customer needs, establishing target specifications, concept generation, concept selection, concept testing, setting the final specifications and establishing a plan for the project. The aim of this phase is to generate and find out which concepts to develop further and plan for this development. This process is seldom linear, and is instead iterative, having steps overlapping during the process. This phase is the main bulk of the development. Here the needs of customers and users are evaluated and ranked, other similar products on the market are examined and used as benchmarks to be able to establish the target specifications for the product. With these specifications in mind concepts can be generated, finding different ways to solve the problem at hand. As stated above the process is divided into several steps, which are:

- Identifying customer needs
- Establishing target specifications
- Concept generation
- Concept selection
- Prototyping
- Concept testing
- Setting final specifications
- Project planning

Identifying customer needs. Identifying customer needs is divided into five sub-steps:

1. Gather raw data from customers.
2. Interpret the raw data in terms of customer needs.
3. Organize the need into a hierarchy of primary, secondary and (if necessary) tertiary needs.
4. Establish the relative importance of the needs.
5. Reflect on the results and the process.

Raw data can be collected through interviews, focus groups or watching the product in use. The raw data is then interpreted as customer needs and ordered into groups of similar needs. After this the relative importance of the needs is established to give a better view of what to focus on during development, and finally the results are reflected upon.

Establishing target specifications. In this step the previously interpreted customer needs should be translated into measurable metrics, and these are in turn ordered by importance, usually depending on the importance of the needs the specific metric satisfies. Focus here lies not on technical solutions, but rather being able to specify metrics to judge future solutions by. Ideally the metrics would be set once in the beginning of the process, but this can be hard for technically complicated products. Instead target specifications are set in the beginning, and later when the constraints set by the product technology are known the specifications can be revised. To get an idea of reasonable target metrics benchmarking is usually done, comparing other available products on the market and using those as a reference point for the new products specifications.

Concept generation. The concept generation can be divided into 5 steps as seen in Figure 3.1

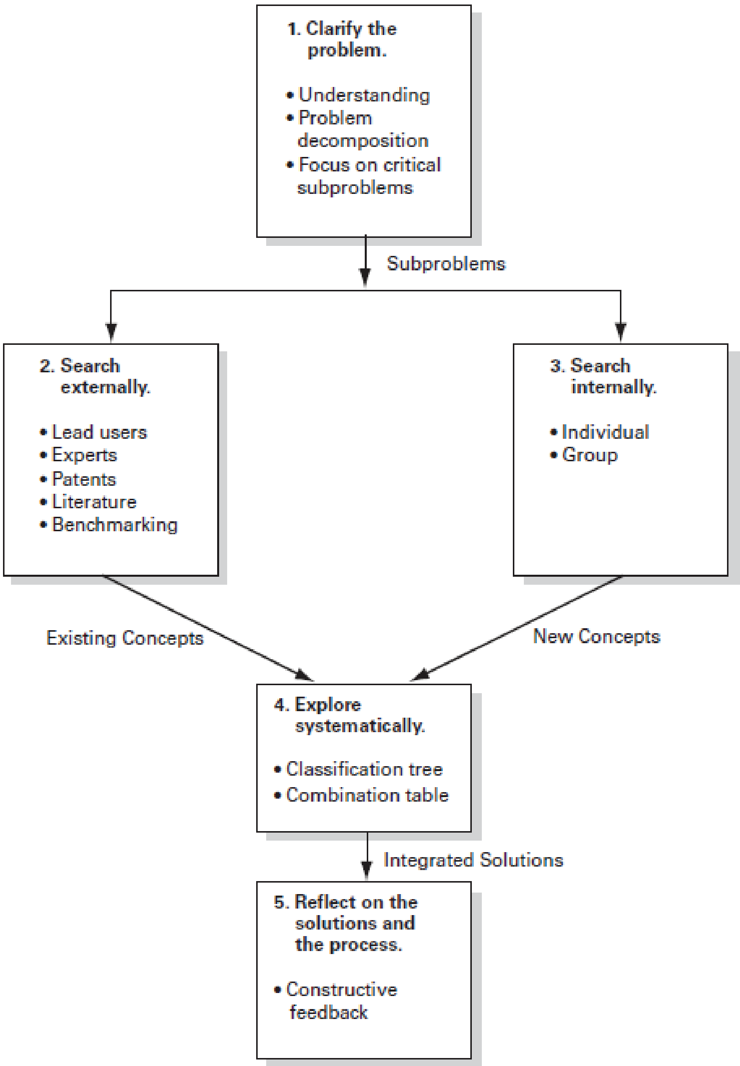


Figure 3.1 The steps of concept generation as seen in Ulrich & Eppinger's Product Design and Development [Ulrich and Eppinger, 2012]

At first clarifying the problem, getting a general idea of it, and breaking it down into subproblems if needed. After this external and internal searches can be conducted to find existing and new solutions to the different subproblems. The solutions to the subproblems can now be systematically explored by combining them for full solution concepts, before reflecting on the process and solutions.

Concept selection. Concept selection consists of picking which concept or concepts to continue with. There are multiple ways to choose the concepts, among them are:

- External decision: The customer or client selects what concept to continue with
- Product champion: An influential member of the product development team chooses a concept based on their personal preference.
- Multivoting: Each member of the team votes for multiple concepts. The concept or concepts with most votes are selected.
- Prototype and test: Prototypes are built and tested and the concepts are evaluated based on the performance.
- Decision matrices: The concepts are scored against pre-specified criteria. The criteria may be weighted.

Prototyping. Prototypes are used to approximate the functionality of the final product in one or more ways that are of interest to the product and development team. This includes many different types of prototypes, from sketches and mathematical models to simulations, test components and functional versions of the product. According to Ulrich & Eppinger prototypes can be classified along two dimensions, the first being between *physical* and *analytical*. Physical prototypes are objects that have aspects of the final product built into them. This can be the look and feel of the product, a piece of hardware to test the functionality of the product or proof of concept prototypes to quickly test ideas. Analytical prototypes instead represent the product in non-tangible ways, usually visual or mathematical. This can include simulations, systems of equations and 3D-models of the product or parts of it. The second dimension prototypes can be classified along is *comprehensive* compared to *focused*. Comprehensive prototypes implement many, or all, of the final products attributes and functions. These are usually full scale, working versions of the product, for example a prototype given to customers to identify any design flaws before producing the product at full scale. Focused prototypes instead implement one or a few aspects of the product. This can include foam representations to investigate the form of the product, or hand built circuit boards to test functionality of the electronics in the product.

When prototyping it a good approach is defining the purpose of the prototype, establishing the level of approximation of it, outlining an experimental plan and finally creating a schedule for procurement, construction and testing. By going through these steps the prototype should have a clear goal and be able to answer the inquiries that were. Depending on what these uncertainties were the prototype should be more or less accurate to the final product, from a single piece to a fully working product.

Concept testing. Ulrich & Eppinger consider concept testing to be tests aimed at the potential customers, where you want the customers response to the product. The concept testing process is then divided into the following seven steps [Ulrich and Eppinger, 2012]

1. Define the purpose of the concept test.
2. Choose a survey population.
3. Choose a survey format.
4. Communicate the concept.
5. Measure customer response.
6. Interpret the results.
7. Reflect on the results and the process.

The first step of a test is defining what question or questions the test should answer, defining the purpose of the test. Common primary questions to answer are which of a group of concepts should be investigated further, how a concept can be improved to meet customer needs better, how many units of the product that will be sold and whether to continue development to name a few.

Next, a survey population should be chosen, deciding who to survey to get as accurate data as possible while still making the survey manageable in size and cost. There are many factors deciding this, some of them being where in the development process the project is, if the data is primarily qualitative or quantitative and what fraction of the target market is expected to value the product.

Depending on the desired data different survey formats can be used. Face-to-face interaction, telephone, e-mail and internet are among the most common survey formats used.

The next step of a concept testing survey is communicating the concept, this can be done a number of ways ranging from describing it verbally, a sketch, videos, simulations or working prototypes to name a few. The choice of survey format and means of communicating the concept are closely linked, seeing as many combinations are simply incompatible. It is also important to consider how the communicated concept is framed and presented, since this will affect the resulting answers and data.

Next is measuring customer response. Early in the process this is commonly done by letting the customer choose between alternative concepts, while further down the design process questions may be asked, where one of the most commonly asked is questions regarding purchase intent ranging from *definitely would not buy* to *definitely would buy*.

When the results are in it is time to interpret them. If choosing between two concepts this can be very straight forward, especially if one is performing markedly better in the concept testing survey. When the results are more even between the concepts the design team might go in and decide what concept to continue with.

Finally the team should reflect on the results and the process. The primary benefit from concept testing is getting feedback from actual potential customers. It can give an early picture of how the product will perform and what needs to be improved without having invested in the full production.

Setting final specifications. The target specifications that were set earlier are revisited after a concept has been tested. The concept can be evaluated and compared to the previously stated targets, and the values of these metrics can be weighted against constraints in the concept as well as trade-offs between performance and cost. This is usually done with the finally selected concepts since these are the closest to the final product and can be compared accurately to the target specifications.

Project planning. As a final activity of the concept development process a development schedule is made to minimize development time and resources. In this plan the resources needed for the project are stated as well as all the specifications, economic analysis of the product, development schedule, project staffing and budget. This acts as an agreement between the development team and management. The project plan is the map for the project, commonly used tools are gantt charts to see the timing of tasks and compare continuously with the reality of the project. The importance of a project plan is not to be underestimated, especially closer to the end of the concept development right before large resources are committed.

3.2.3 System-level design

The system level consists of product architecture and decomposition of the product into sub-systems and components. It may also contain first plans for the production system as well as final assembly. The output of the phase is usually functional specifications of the products subsystems, geometric layout of the product as well as preliminary process flow diagrams for the final assembly process.

3.2.4 Detail design

In the detail design phase the final part geometry is defined as well as tolerances and materials of the components. What standard parts should be bought from manufacturers and what needs to be built specifically for the product. The output is a complete control documentation for the product. It contains drawings or files describing the part geometries, tooling, tolerances, quality control, specifications for purchased parts and process plans for fabrication and assembly of the product.

3.2.5 Testing and refinement

The testing and refinement phase consists of constructing and testing multiple prototype versions of the product. Early prototypes are usually built with parts with the same geometry and materials of the intended final product but produced by different means. These prototypes serve to determine whether the product will work as intended or not and whether it satisfies important customer needs. Later prototypes can be made from parts produced in the intended way but not necessarily assembled using the final intended assembly process. These prototypes are thoroughly evaluated and often tested by customers. These tests are done to identify necessary engineering changes for the final product before full production is started.

3.2.6 Production ramp-up

The production ramp-up is where the product is produced with the intended production and assembly systems. The purpose is to train the workforce and solve any remaining problems in the production process. The change between production ramp-up and full production is usually gradual and at some point in the process the product is launched and made publicly available.

3.3 IDEO human centered design process

IDEO is a design company focusing on human-centered and interdisciplinary design. The company is from the US but has studios in Europe and Asia as well. They practice something they call human centered design, which focuses on the end user, or human, at the end of the product. To give insight in how this process works and is used they have created The Field Guide to Human-Centered Design [Ideo, 2015]. The book includes the thought process behind their design process as well as practical tips and exercises.

3.3.1 Inspiration

The first step of IDEOs human.centered design process is the inspiration phase. Here focus lies in collecting information. It includes framing the design challenge, defining what problem is to be solved, and it focuses heavily on interacting with people, especially end users, by interviewing people, groups and experts, defining the audience for the product, as well as understanding the audience and end users.

3.3.2 Ideation

During the ideation phase all the knowledge gathered in the inspiration phase is made sense of, formulating opportunities and design possibilities. Ideas will be generated, tested and prototyped, to then be shown to the people you learned from during the inspiration phase. With their feedback you can iterate, refine and make the solution ready to be launched. The work is iterative, always getting new input from end users and key people to improve the final product.

3.3.3 Implementation

In this phase the final product is launched and brought to market. With all the input during the whole process the idea is that the solution will succeed since you have already gotten input to make sure that the product is what the customers want. In the implementation phase you also refine the business model and build partnerships. It is the whole marketing process, from pilot program to a finished product with it is corresponding business model.

3.4 Double Diamond

The double diamond model is a design process created by the British Design Council in 2004 and evolved in 2019 [British Design Council, 2019]. It consists of four stages of divergent and convergent thinking to exhaustively explore and select the best solutions for a problem. The stages are Discover, define, develop and deliver. The process can be seen in Figure 3.2 but unlike in the diagram the process is not linear, but rather it is iterative, often going back to previous steps with new information gained in the later stages. [British Design Council, 2019] [Costa, 2018]

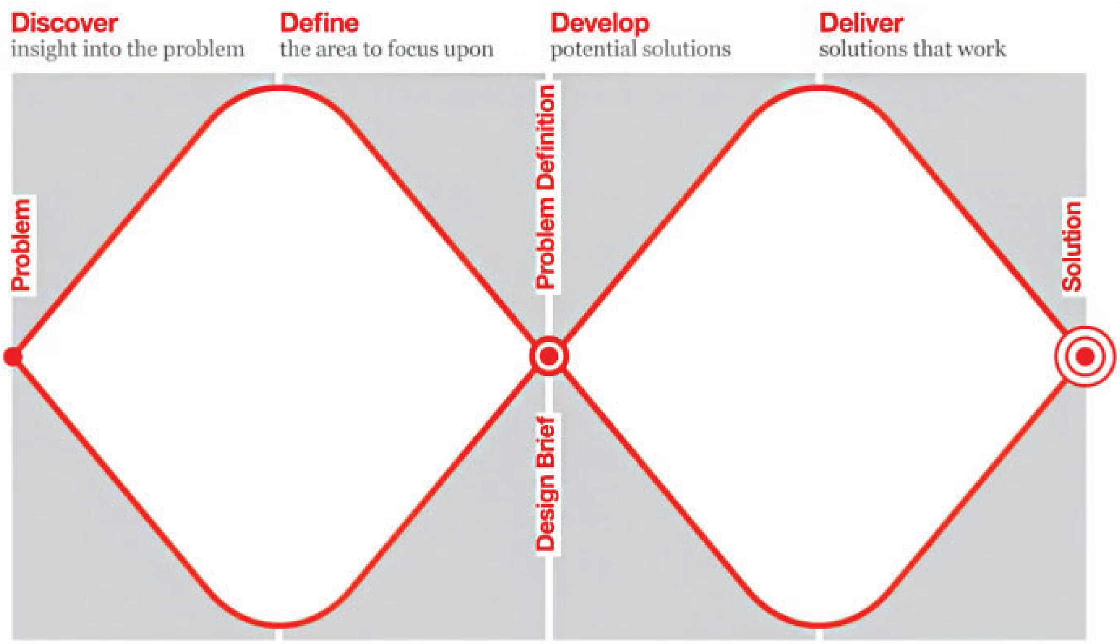


Figure 3.2 An overview of the double diamond design process from [Costa, 2018]

3.4.1 Discover

In the discover phase the problem at hand is analysed and explored to find out what the key issues are. It consists of talking to people affected by the issue, and studying the problem from multiple angles. The goal is to clarify the problem and put it into context.

3.4.2 Define

The information gathered in the discovery stage is used to more precisely define the problem or opportunity. Bottlenecks and resource waste are identified, hidden opportunities discovered, and the different subproblems and components of the problem are defined.

3.4.3 Develop

This is where the actual designing comes into place, finding different solutions to the defined problem, again diverging to get as many solutions as possible. Designers use the help of internal partners, like engineers, developers or any other people or departments with useful experience within the project to find the best solutions.

3.4.4 Deliver

Deliver includes testing of the different solutions, rejecting those that do not work and continuing development of those that show potential. This is the final step before getting a go from the higher ups and launching a product. [British Design Council, 2019] [Costa, 2018]

3.5 Choosing a product development process

To begin with, different product development processes were looked at using the one outlined by Ulrich & Eppinger in Product Design and Development [Ulrich and Eppinger, 2012] as a base since this was the process the authors had the most experience with. Along with the process described by Ulrich & Eppinger other design processes were investigated including Double Diamond [British Design Council, 2019] [Costa, 2018] and IDEO Human Centered Design Process [Ideo, 2015]. The IDEO Human Centered Design Process focused heavily on the end user and interacting with the end users and their input. Since the scope of work was for a prototype and the main customer were ASSA ABLOY rather than the very end users the IDEO design process was deemed unsuitable for this work. Inspiration was taken from the Double Diamond design process adding the first steps onto the Ulrich & Eppinger product development process. The first step, discover, consisting of reading up on and familiarizing with the subject was added as the first step. After doing this, getting to know the subject, current solutions at ASSA ABLOY, as well as other solutions and technologies available the process outlined by Ulrich & Eppinger was followed until a final prototype was made. The final design process used was the following

1. Discover
2. Product Planning
3. Concept Development
4. System-Level Design
5. Detail Design
6. Testing and Refinement

The final step of Ulrich & Eppinger, Production Ramp-up, was left out since the scope of work was to make a functioning prototype and not actually starting production of the product.

4

Product development

In this chapter the working process of the project is described in accordance to the process first mentioned in section ***3.5. Choosing a product development process.***

4.1 Product planning

The very first step of the process was setting the limitations of the project. Much of this had already been done by ASSA ABLOY so there was no need to survey the market opportunities, but rather declare a mission statement with goals, constraints, and assumptions. The end goal for the project was to create a working prototype of an encoder for the motors of the high speed doors at ASSA ABLOY. The encoder had to have sufficiently high resolution and attach to the motor rather than the output shaft of the roll up door. The scope also did not include production of the final product, although the producibility of the final solution was considered as well as a simple cost analysis comparing cost to similar solutions available on the market. In the solution both the actual encoder, meaning the sensors and electronics, as well as the physical connection to the motor was to be included without making any changes to the motor.

4.2 Identifying customer needs

As a first step in the process the customer needs had to be specified. Since the encoder would be used by ASSA ABLOY as part of a system which they both sell and install, they would be the main customer and provide the most valuable input. By talking to experienced employees at ASSA ABLOY this resulted in some very precise requirements, and a couple of vague ones. These are presented in Table A.1 in Appendix A.1, where the left column contains the statements made and in the right column the interpreted needs related to the statements that are presented. The needs were generated by trying to break down the original statements to more measurable needs and interpreting what characteristics the product would need in order to fulfill them.

The needs were then divided into subgroups to gain a clearer overview of the different needs. When divided they were graded by their relative importance. This was done on a 1-3 point scale at first, but then on a 1-5 point scale instead to give a more precise rating of importance. A higher number is more important and lower numbers are less important. Both the groupings and importance scores can be found in Table A.2 in Appendix A.1. The scores were established through discussions with supervisors and amongst the authors, taking the requirements of ASSA ABLOY and the current system into consideration.

4.3 Establishing specifications and requirements

To be able to use the customer needs in the development process a list of metrics for the different needs was created, along with the units to be used for each metric. These needs are presented in Table A.3 in Appendix A.1. Some of the units are specified with SI-units while some are binary, or subjective if there is no apparent way of measuring the values.

4.4 Benchmarking

After the metrics for the customer needs had been set the next step was to benchmark the metrics by analyzing already existing solutions. This was done to get an idea of what values could be appropriate and to aid in the process of setting parameters when generating ideas for the solutions. The market was surveyed for competetive products to benchmark against. The products chosen were in the middle price range of encoders found and consisted of a capacitive encoder, a magnetic encoder and an optical encoder. These products would reasonably reflect what could be expected in terms of function from a general purpose motor encoder and in addition these products covered 3 out of 4 main technical solutions available in today's market which could have been used in the implementation for the high speed doors. The fourth technical solution, which has been left out, is a mechanical encoder. From what the authors gathered mechanical encoders does not hold a large market share for these kinds of applications and as such is not as relevant to benchmark. The benchmarked products and their respective values are presented in Table A.4 in Appendix A.1.

After gathering data from exisiting products on the market, benchmarked values were set for the prototype to be developed. A worst accepted value, an optimal value and a target value were set for the metrics where data had been gathered which can be seen in Table A.5 in Appendix A.1. For the metrics where no data was available for the benchmarked products, or there were no clear specifications of needs from ASSA ABLOY the field was simply left empty. These benchmark values were set as a guideline for the project and were not set in stone to allow for flexibility in the process as well as to accommodate for any changes or new discoveries later in the project.

4.5 Concept generation - initial sensor technology & mounting method

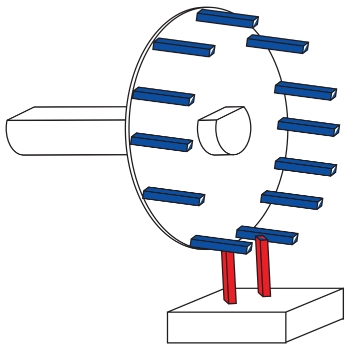
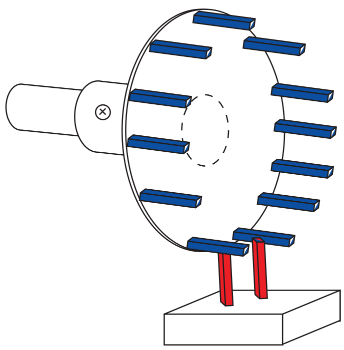
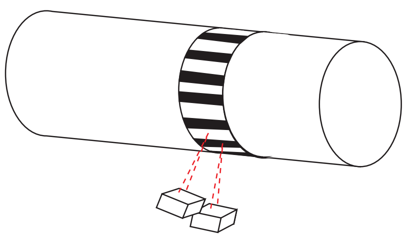
With the specifications and requirements set the concept generation was started. In order to gain a first set of concepts the authors began with brainstorming individually with the established requirements in mind, to achieve a set of concepts without being too influenced by already-existing encoders. The generated concepts were then discussed with each other and a quick evaluation was performed. The ones that were very similar were combined, ones that seemed unreasonable were eliminated and the ones that seemed plausible were kept until the next step. To further increase the concept pool the current market was also explored to see what competitive solutions were currently available.

When generating the concepts it was found that a lot of the solutions had similar technical measurement solutions only with different methods of attaching the encoder to the shaft. Because of this the problem was divided into two sub-problems: attachment method and measurement technique. These sub-problems were explored further and each sub-problem was divided into a couple different solutions and placed in a combination matrix to evaluate possible solutions combinations. The matrix can be seen in Table 4.1, where the measuring techniques are listed on one axis and attachment methods on the other. The combinations were then evaluated and color-graded to see which ones could be good solutions (green), which were plausible but not great (yellow), and finally, which ones were considered bad (red). In the green cells the generated concepts, found in Table 4.2, connected to that specific combination are numbered. This matrix resulted in 18 combinations that were considered good and a total of 32 concepts when also taking the brainstorming solutions and variations of the combinations into consideration. Simple drafts were created of each concept in order to get a visual representation for each concept, and help in the process of selecting which concepts to continue with. The concepts that were created are presented in Table 4.2.

Table 4.1: Combination matrix of fastening methods and sensor technologies

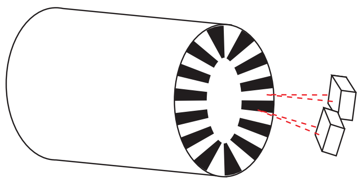
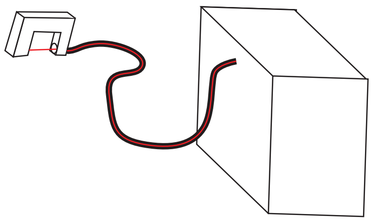
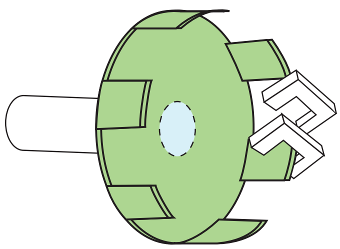
Type of sensor / Type of connector	Mechanical	Optical	Magnetic	Capacitive	Resistive
Click-on				27	
Screw block		32			31
Tape		3, 4			
Glue		6, 7, 8	15	18, 19, 20	
Press fit		12, 13, 14	16	24, 25, 26	
Slide-on	1	9, 10, 11	17	21, 22, 23	
Fork standoff	2			28	
Threaded shaft				29	
Moved out		5			

Table 4.2: Concept drafts

Concept no.	Concept draft	Description
1		Spinning wheel with mechanical connection, slide on motor shaft connection
2		Spinning wheel with mechanical connection, forked standoff connection to the motor shaft
3		Optical encoder with reflective tape on motor shaft

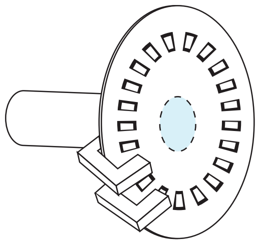
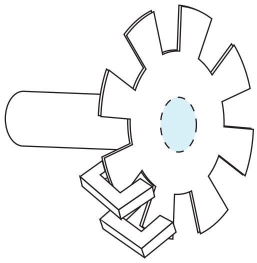
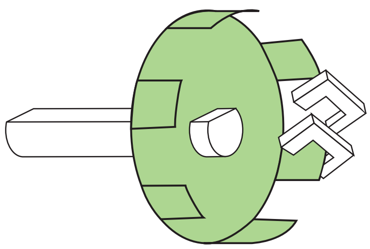
Continued on next page

Table 4.2: Concept drafts (Continued)

4		Optical encoder with reflective tape on motor shaft end
5		Optical encoder with fiber-optic cable to have measurements in a different location
6		Optical encoder with a forked wheel, glued on motor shaft end

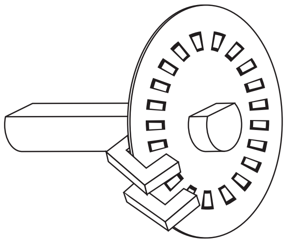
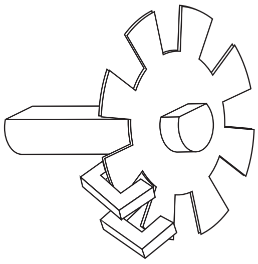
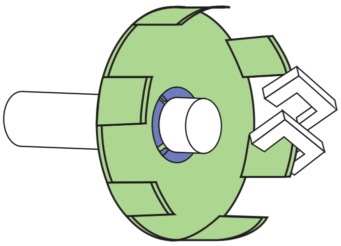
Continued on next page

Table 4.2: Concept drafts (Continued)

7		Optical encoder with slit-plate, glued on motor shaft end
8		Optical encoder with forked plate, glued on motor shaft end
9		Optical encoder with a forked wheel, slip-on motor shaft connection

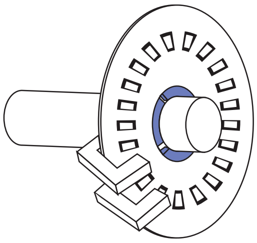
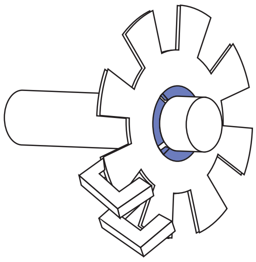
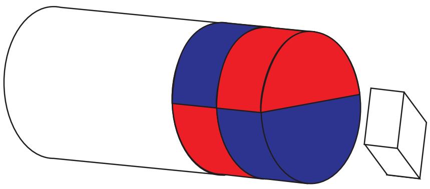
Continued on next page

Table 4.2: Concept drafts (Continued)

10		Optical encoder with slit-plate, slip-on motor shaft connection
11		Optical encoder with forked plate, slip-on motor shaft connection
12		Optical encoder with forked wheel, press-fit on motor shaft

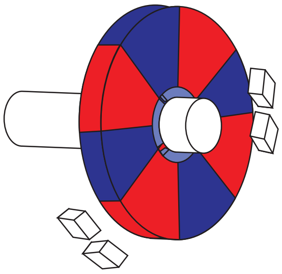
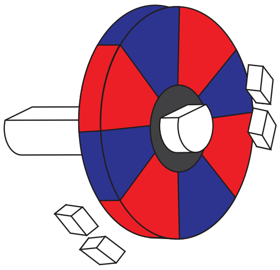
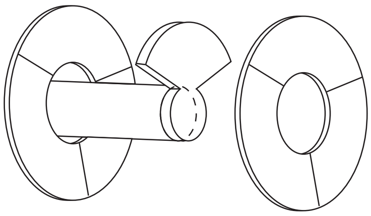
Continued on next page

Table 4.2: Concept drafts (Continued)

13		Optical encoder with slit-plate, press-fit on motor shaft
14		Optical encoder with forked plate, press-fit on motor shaft
15		Magnetic encoder, with hall effect sensors, glued on motor shaft end

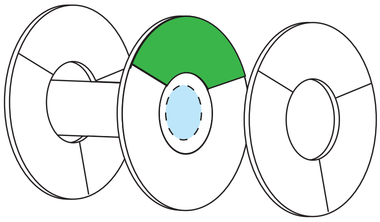
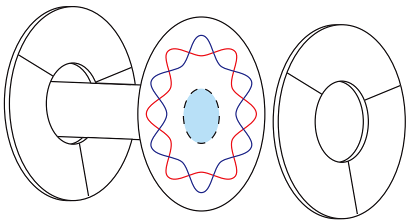
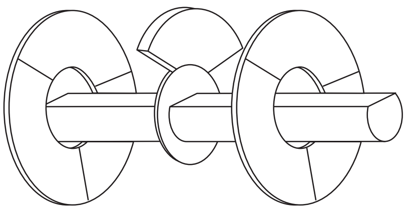
Continued on next page

Table 4.2: Concept drafts (Continued)

16		Magnetic encoder, with hall effect sensors, press-fit on motor shaft
17		Magnetic encoder, with hall effect sensors, slip-on on motor shaft connection
18		Capacitive encoder with circle sector rotor glued on motor shaft end

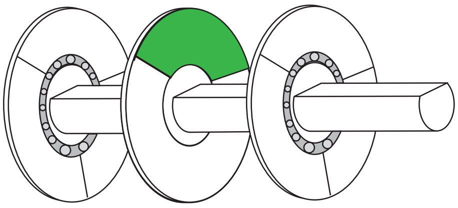
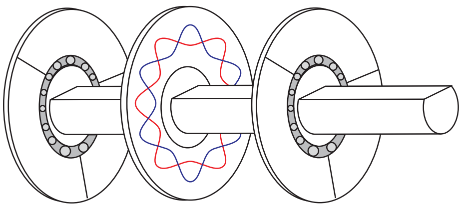
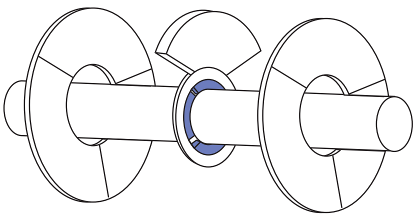
Continued on next page

Table 4.2: Concept drafts (Continued)

19		Capacitive encoder with circle sector rotor of two materials glued on motor shaft end
20		Capacitive encoder with sine wave rotor glued on motor shaft end
21		Capacitive encoder with circle sector rotor, slip-on motor shaft connection

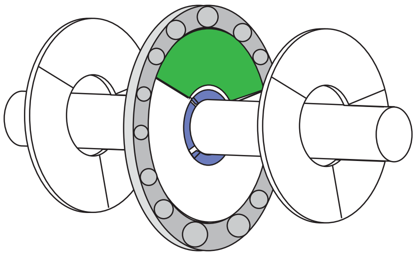
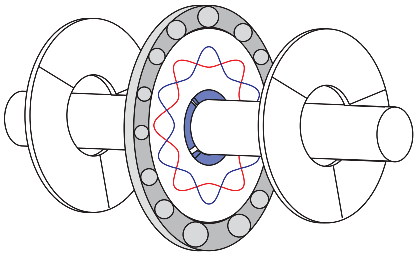
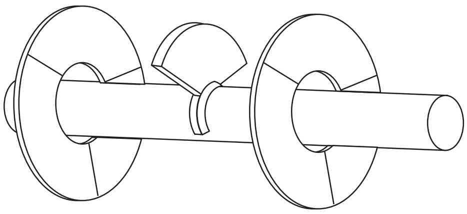
Continued on next page

Table 4.2: Concept drafts (Continued)

22		Capacitive encoder with circle sector rotor of two materials, slip-on motor shaft connection and bearings connecting the shaft to the stators
23		Capacitive encoder with sine wave rotor, slip-on motor shaft connection and bearings connecting the shaft to the stators
24		Capacitive encoder with circle sector rotor press-fit on motor shaft

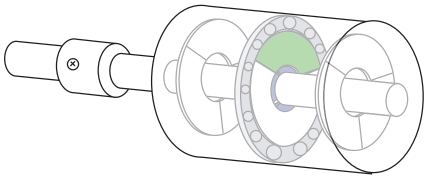
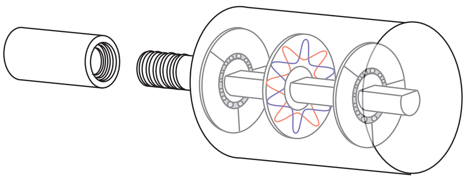
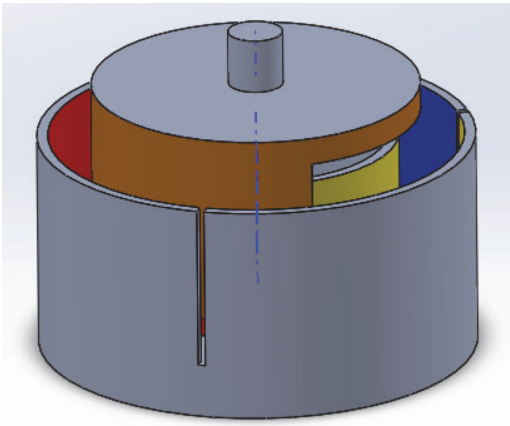
Continued on next page

Table 4.2: Concept drafts (Continued)

25		Capacitive encoder with circle sector rotor of two materials press-fit on motor shaft with a central bearing holding the rotor
26		Capacitive encoder with sine wave rotor press-fit on motor shaft and a central bearing on the rotor
27		Capacitive encoder with circle sector rotor, click-on motor shaft connection

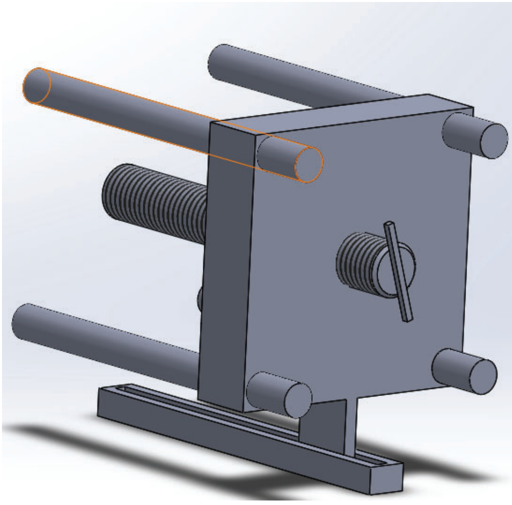
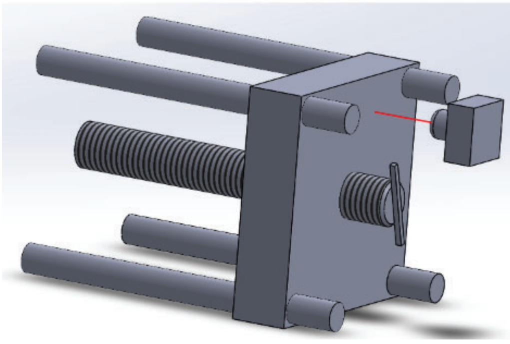
Continued on next page

Table 4.2: Concept drafts (Continued)

28		Capacitive encoder with circle sector rotor of two materials, screw-press on motor shaft connection and a central bearing connecting rotor to housing
29		Capacitive encoder with circle sector rotor, threaded screw on motor shaft and bearings connecting the shaft to the stators
30		Capacitive encoder with cylindrical parts

Continued on next page

Table 4.2: Concept drafts (Continued)

31		Screw transmission to resistive sensor
32		Screw transmission with distance sensor

4.6 Concept selection

The process of deciding which concepts to continue developing was done in collaboration with experienced engineers at ASSA ABLOY. The project and identified sub-problems were presented to them, as well as all the concepts. After the presentation the different concepts and their pros and cons were discussed, and finally the concepts to continue with were picked. In terms of sensors it was decided to look into solutions using optical encoders, mechanical encoders and capacitive encoders, in that order of relevance. It was however decided not to use reflective optical encoders with concerns to how they would hold up in dusty industrial environments. By the same reasoning the slit-discs were decided to not be continued with, since they provide the same functionality as the cog-design, but with higher risk of disturbances from dust. Other than that, the specific designs were not set, since the optimal design could vary depending on the mounting and housing solutions, so it could be limiting to decide on a specific design this early. Considering the way to mount the encoder to the motor shaft it was decided that the best way to move forward was using a friction fit solution, preferably one that would be universal for a range of standard motors used at ASSA ABLOY. All of these decisions were based on the discussion and opinion of the experienced engineers present at the concept selection meeting without the need for voting.

4.7 Concept generation - encoder shaft

After some concept generation for connectors to the motors new information regarding the connection between motor and encoder was discovered. On all motors there was a 6mm hexagonal hole at the back of the motor where the encoder would attach rather than a protruding round shaft. This changed how the connection between motor and encoder could work as a previous assumption had been that the encoder would attach to a protruding cylindrical shaft. The concept generation done for connections to a cylindrical shaft can be seen in Appendix B.1. The new attachment led to solutions where a shaft would be inserted into the hexagonal hole of the motor were evaluated.
With the new information regarding the connection for the encoder to the motor and a functional motor available the motors were examined again. It was decided that some key considerations for the new type of connection were that all current functions should still be available with the encoder connected. These functions were the possibility to manually turn the motor, as well as an off switch when a crank for manual turning was attached to the motor to avoid the motor running and potentially injuring the user or breaking something. An important detail with the new connection was that all motor models had the same size of hexagonal hole, removing the need for a connection that could attach to multiple sizes of shafts. With regards to the previously mentioned traits a couple of parameters for the designs were set up. To meet the requirements of the set ingress protection (IP) rating while maintaining the rotation capabilities either a ball bearing or a plain bearing would be required, thus needing either partly circular sections of the axis or some adapter on the hexagonal section. It was also stated that if an optical sensor was to be used the forked wheel used by ASSA ABLOY in another motor would be used to simplify logistics and remove the need to create new tools for a very similar part. To generate concepts for the shaft a discussion was held, first of all concerning what needed to be solved by the shaft and what restrictions were already set. The restrictions and problems to be solved by the shaft were the following:

- 6mm hexagonal shaft in the motor connection end
- 6mm hexagonal hole in the non motor end
- Enable rotation between shaft and housing
- IP rating, making sure it’s sealed from dust & water between the shaft and housing
- A way to connect any rotating parts of the encoder
- Rotating encoder parts should be in a known position on the shaft in axial direction

- The whole encoder should be assemblable
- The shaft should be compatible with the existing forked wheel used at ASSA ABLOY

With these restrictions, solutions were generated for each sub-problem and continuously checked with previous solutions so it could all work together without interference between solutions. The ends were the easiest to decide how they would look since there was very little choice given. One end would be a 6mm hexagonal shaft and the other would be a circular shaft with a 6mm hexagonal hole. It was decided that the outer geometry of the shaft would be circular in both ends since this is a very commonly used geometry for bearings. This would in turn lead to a wide range of bearings to choose from, allowing for a better rotational solution with both better fit and seal against dust and water.
For connecting the rotating parts of the encoder, either the rotor for a capacitive encoder, or an encoder disc for an optical encoder, it was at first decided to simply friction fit the disc to the motor shaft. This was what had been discussed earlier in 4.6 during concept selection when designing for a protruding shaft which was plan when the information given was that a protruding shaft would be present from the motor. When it was found that it instead a separate shaft in the encoder should attach to a hexagonal hole in the motor, there was no reason to change the way the encoder rotors would connect to the rotating shaft in the encoder. To make sure the position of the rotor/encoder disc was known the disc could either be slid all the way to the transition between the shaft and the thicker bored shaft, or a lip could be added as a stop. This would also help with assembling, having a simple way to know the rotor is in the correct position.
Depending on what type of encoder technology would be used the assembly would be more or less simple. With an optical encoder with a forked wheel the assembly would be the easiest since the encoder disc could be slid on and then the whole shaft could simply be slid into the housing with the photosensors being connected in the axial direction. With a forked disc it could be a bit more complicated since the photosensors would need to be attached from the side in the radial direction to the shaft meaning the shaft could not simply be slid with the forked disc into the housing and fitting to the sensors. Using a forked disc would also possibly lead to the need of curved printed circuit boards (PCB) or two separate PCBs for the sensors placed at diffferent angles to the shaft. This in addition to the want from ASSA ABLOY to use their already available forked wheels led to forked plates being disregarded.
The most complicated assembly would be with a capacitive encoder since this requires at the least one rotor and one stator, possibly two stators which should surround the shaft without touching it. There are solutions to this but simply the number of pieces to connect without interfering with eachother would make the assembly more complicated. No matter the solutions for assembly this would mostly affect the housing and not the shaft, and so a design was decided for the

shaft, and the different problems that could arise depending on what encoder technology was used would be solved by the design of the housing. The first solution decided on for the shaft to prototype was a transition as the following: 6mm hex shaft - thin round shaft - (lip for spacing) - thick round shaft with a 6mm hex hole.
A drawing of the design with and without a lip can be seen in Figure 4.1

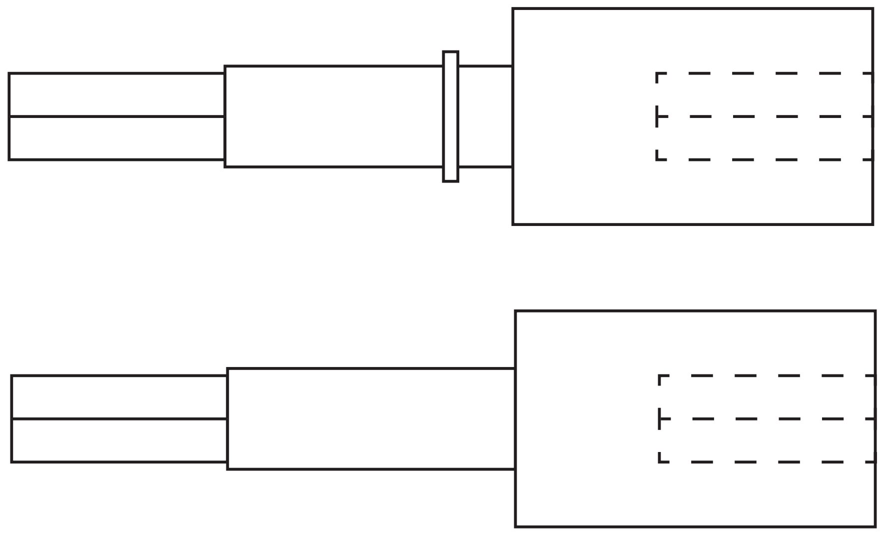


Figure 4.1 Drawing of the shaft concepts, one with a lip for spacing of rotating encoder discs and one without.

Later it was discussed and decided to make the diameter of the circular parts of the shaft connecting to the housing be the same diameter. This was to reduce the number of articles needed allowing to use the same type of bearing in both ends, if two bearings were to be used, giving both logistical and economic gains for ASSA ABLOY. It was also decided to have the ends connecting to the housing slightly smaller than the shaft within the housing since this would help with connecting the bearings giving them an absolute position and be easier to press fit onto the shaft.
When the drawings of the already existing forked wheel were made available there were some adjustments in width to accommodate for it, as well as a flat face added for the connection between forked wheel and shaft. Simulations were also made for the expected forces that the shaft would be exposed to, in order to make sure that it would be rigid enough. These simulations can be found in appendix C.1.
As a final step discussion was held with engineers at ASSA ABLOY where it was stated that to hold the shaft in place a single bearing would be enough rather than one on each end, depending on sealing solutions in the ends. The main idea was to have the bearing at the motor side of the encoder since this would give more flexibility when concept generating for the housing.

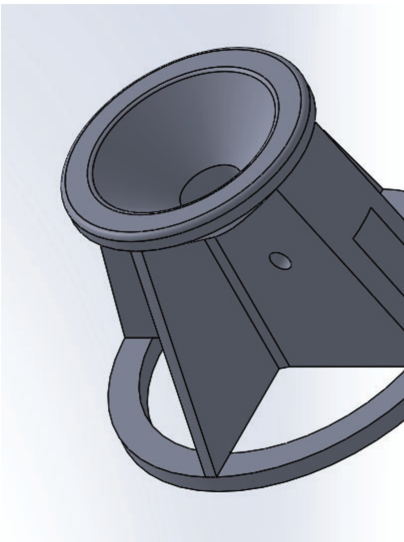
4.8 Concept generation - encoder housing

With the sensor technology and encoder shaft design being determined, the next step was concept generation for the housing. Naturally, all of the product specifications were taken into consideration during this step, but the main ones that needed to be solved by the housing were the IP rating, the mounting to the motor housing and the physical stress criteria. This is due to the housing providing protection to the encoder, as the sensor technology can be rather sensitive to outside disturbances. From discussions with knowledgeable people at ASSA, it was determined that a capacitive encoder would require rating IP54, maybe even as low as IP44, and that an encoder with optical technology would require a higher IP rating of at least rating IP65 due to the higher sensitivity to dust.
In a similar way to the shaft, the restrictions and problems to be solved by the housing were listed as follows:

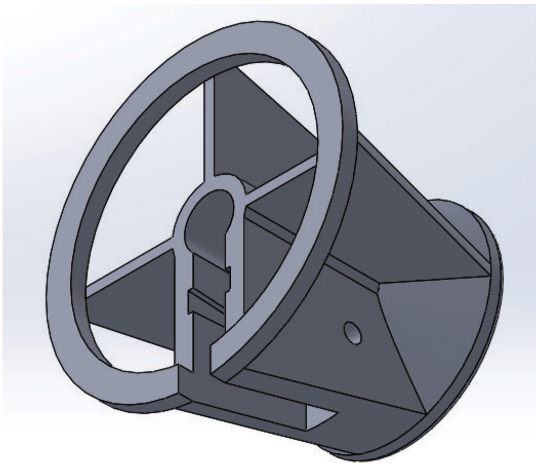
- A sensor recognizing when the crank for manual driving is inserted and, preferably, when something else is inserted as well, for example a finger.
- A bearing or rotation solution for the shaft to be able to rotate freely
- Keeping out dust and water from sensitive components
- Output and input cables
- Spacing for encoder discs
- Assemblability of the encoder unit
- Mounting solution between motor and housing/encoder unit
- Being able to open the housing for assembly and service

Shaft sensor. For the shaft sensor it was thought that the simplest and most affordable solution would be using a micro switch since this could be engaged by any physical object being inserted into the housing, not only the shaft of the manual crank. Other options such as inductive or capacitive sensors were discussed but these had more unnecessary restrictions (only recognizing metal objects) and were much more expensive than a micro switch. An optical sensor would not be used since it would work poorly in dusty and wet environments.
To reduce the risk of water and dust entering the housing and disturbing sensitive electronics it was also decided that the micro switch would have its own part of the housing since it has to be engaged physically and therefore can not be completely enclosed. There are micro switches available with high IP rating that could be used without having them enclosed from the environment which made this solution possible. The micro switch would be of a type with equal or higher IP rating than the rest of the encoder unit to keep the original rating of the full product. For this

solution an additional attachment was designed, which was to be placed on the encoder side where a manual crank would be inserted. This design can be seen in Figure 4.2. In this attachment the micro-switch would be inserted through the bottom, fastened by a small pin and then the whole attachment would be fastened to the housing. The micro-switch with rating IP67 and the cross-section of the attachment where the micro-switch would be attached is displayed in Figure 4.3 and a schematic assembly to the rest of the encoder housing can be seen in Figure 4.4.

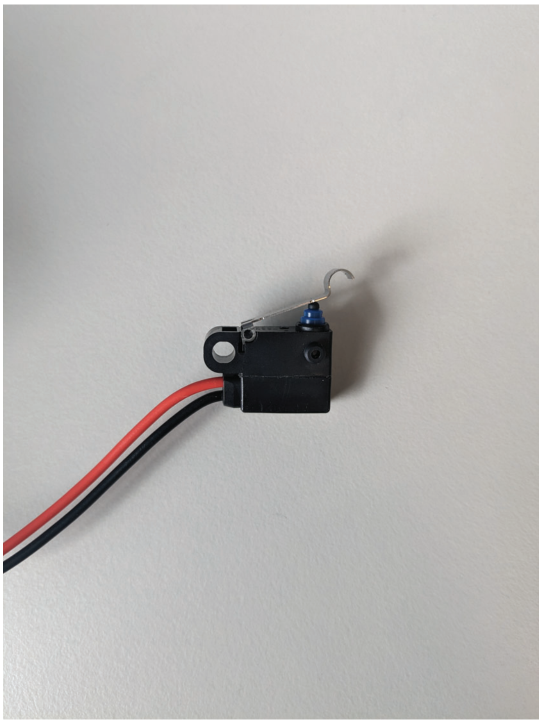


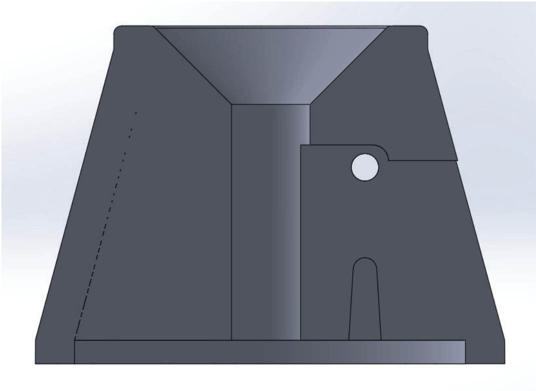
(a)



(b)

Figure 4.2 The attachment for holding the micro-switch in place to detect any objects entering the encoder seen from the top (a) and bottom (b)





(a) **(b)**

Figure 4.3 The micro-switch with rating IP67 which would be used (a) and a cross-section of the holder where the micro-switch would be fastened (b)

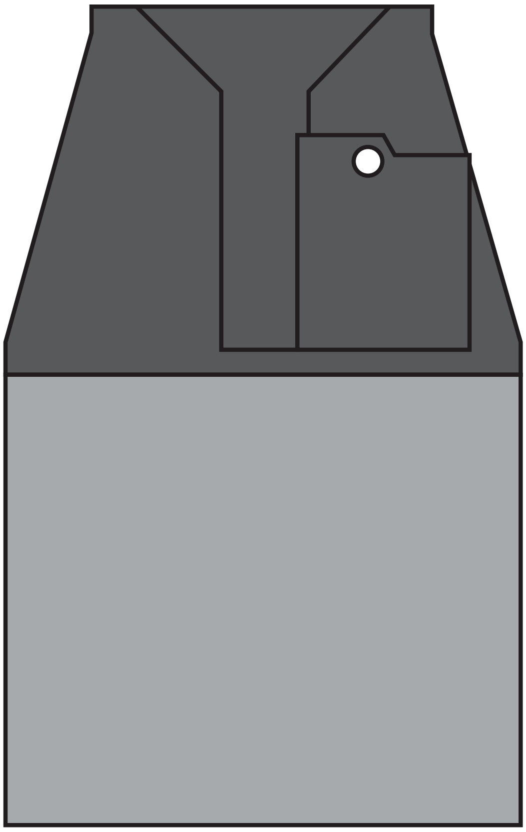


Figure 4.4 A schematic assembly of the micro switch holder (dark grey) attached to the end of the encoder housing (light gray)

Later it was also discussed to, instead of using a micro switch, add a lid over the opening facing away from the motor. This lid would have a sensor sending a signal when the lid was opened and switch off the motor at that point. The lid could also be easily sealed using O-rings leaving the option open to only have a single bearing at the motor side of the encoder. The concept for the lid was added at a later state and thus generated as an addition to the main housing. Since the hold for the micro-switch was created as a separate part anyway this led to it being as simple as replacing the micro-switch housing with a sliding lid, accompanied by a sensor on the PCB close to the lid and side facing away from the motor to recognise when the lid was opened.

Rotation of the shaft. To make sure the shaft could rotate freely the simplest solution would be plain bearings with lubrication connecting the housing and shaft, using either plain bearings or ball bearings. It would need to be tested to see if these would give a good enough seal against dust and water. If they would not seal enough, additions could be made, either using another type of bearing or adding radial seals.
One important thing that was considered was how to know the position of the shaft in relation to the housing so as to know at what distance the rotating encoder discs would be, compared to their optical sensors or stator discs. One idea to solve this

was making the plain bearing for the hole end of the shaft according to Figure 4.5. This way the shaft could be completely slid into the bearing while still leaving a hole for the manual crank to fit in. The shaft and bearing could then be slid all the way into the housing stopping at the end thanks to the flanges of the bearing. With the length of the shaft being known and now the position of one of its ends also being known the position of the rotor discs would also be known. One possible problem with this could be that different motors need different length of shafts. However this difference was only 1.5 mm and it was decided that the shaft could always be of the shorter length and simply have 1.5 mm less gripping distance in the motors with longer hex holes which would not make any significant difference for the function or durability of the encoder or motor.

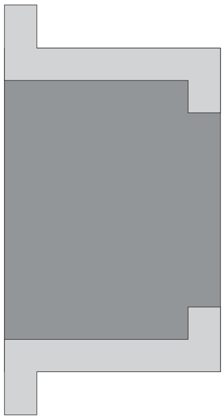


Figure 4.5 A plain bearing design that allows for a shaft to be inserted all the way as to ascertain the exact position of the shaft in relation to the housing where the bearing is attached

After the authors concept generation and discussion with engineers at ASSA ABLOY it was decided that the detail design of the seals and bearings would be developed with outside input from an external company. This was to make sure the solution would be the best possible one for the product, and since the company in question are suppliers for ASSA ABLOY they would need to be involved at some point either way. A discussion was initiated with the supplying company and some requirements for the bearing and sealing solution were stated:

- Maximum of 0.4 Nm tangential friction
- A life-span of at least 65.000.000 rotations
- A water and dust seal according to rating IP65
- A permanent lubrication upon assembly, ie no additional lubrication needed after assembly

In addition to this it was said that emphasis should be put on finding a low cost solution and also that the bearing in question would not need to handle much force since it would only hold the weight of the shaft, which would end up in tens of grams. This discussion was initiated later in the project and therefore no final solution was completed and supplied from the company and the final sealing was left as future work.

Dust & water seal. One main function of the housing of the encoder was to keep a tight seal from dust and water, protecting the sensitive electronics measuring the angular velocity of the motor. This is especially important if using photosensors for the encoder since dust could severely impact their function. If using capacitive sensor technology this seal would not have to be as tight. Since it was not certain which technology would be used it was opted to go for a tighter seal in case the more sensitive photosensors would be used. The housing would then have to pass an IP65 classification.
To achieve this seal the number of possible openings or cracks should be reduced to a minimum. The openings that would have to be present were, first of all, the two holes for the shaft, some opening for a cable for electricity and output signals as well as a way to open the encoder housing, at least before assembly.
The holes for the shaft would be sealed by some type of bearing since the shaft would still have to be able to rotate. If the end lid would be used that would need to be fastened and sealed in the closed position, preferably using a simple O-ring solution. For the cables there are multiple solutions on the market so this was put on hold as it was assumed that there would be a solution for it that would work, but a preliminary idea was to use a cable gland since this is easily available, affordable and simple.
One important aspect to keeping a good seal if the micro-switch would be used was to separate the main encoder electronics and the shaft sensor since the micro-switch depended on having an opening to the outside big enough for a 6mm hexagonal crank to fit in. This also meant that the cable for the micro switch would be separate from the other cables to avoid needing another opening in the main housing.
The last thing to seal would then be the opening for assembly. It was discussed where to have this opening and finally decided that the opening would be in the axial direction of the shaft since this would simplify assembly quite a bit. Since the shaft would need to be longer than the housing an opening on the "long" side of the housing would not allow for the shaft to be put into the housing unless the shaft was made in two separate pieces and assembled inside the housing. Therefore it was decided not to have the opening on the long side. The main sealing solution discussed for the assembly opening was an O-ring in a groove sealing the slit between inner housing and an end cap.

Output cables. There would need to be an output cable from the main housing to the control unit. If the micro-switch solution would be used there would either need to be a cable running from the switch into the main housing, or the encoder unit would have two output cables, one from the micro switch and one from the main housing and encoder sensors. A request from ASSA ABLOY when this was discussed was to only have a single output cable from the encoder unit since this would make the connection to the control unit a lot simpler. In this case there would have to be another connection for cables to the main housing which is undesirable from a complexity perspective. If instead the sliding lid with a sensor would be used for safe manual drive, the sensor would be inside the main housing leading to there only needing to be a single output cable from the main housing with no other cables connecting to it.

Spacing for encoder discs. If a photosensor based encoder would be made the spacing would be quite simple with only a rotor disc needing to be correctly spaced in relation to the PCB within the housing. This positioning could be done in multiple ways, with lips or edges on the shaft. With the forked wheel in a known position the photosensors could simply be put at one end of the housing with the rotor disc at the correct distance away.
If using capacitive technology for the encoder there would not only be a rotor plate but also one or two stator plates depending on the chosen solution. This would lead to a similar solution for the rotor disc with the addition of the stator plates. Two main solutions were discussed as viable, one being that the housing would be split in the middle rather than on one of the ends and have the stator plates being slid into one half each and then putting the housing together. The other solution was to have grooves within the housing along the shaft axis that the stator plates would fit into and simply be slid into their correct position (one having a stop earlier than the other if two plates would be needed) This would lead to a "stacked" assembly where the first stator would be slid into place, the shaft with a rotor would be put into the housing, and then finally the second stator would be slid into place with a spacer holding the first stator in place as well.

Assemblability of the encoder unit. As the solutions for the different problems were generated it was continously checked that these would be able to be assembled as well. It was noted that it would be simpler to assemble an encoder using optical sensors and a forked wheel given that this would require no additional grooves inside the housing for stator plates. The PCB would simply be attached to the inside of one of the ends of the encoder house. While it would be more complicated it would still be possible to assemble an encoder using capacitive sensors with a solution needing only one stator plate being easier to assemble than one using two stator plates. The simplest assembly solution for solutions with stator plates would be grooves along the inside of the housing and using a "stacking" assembly.

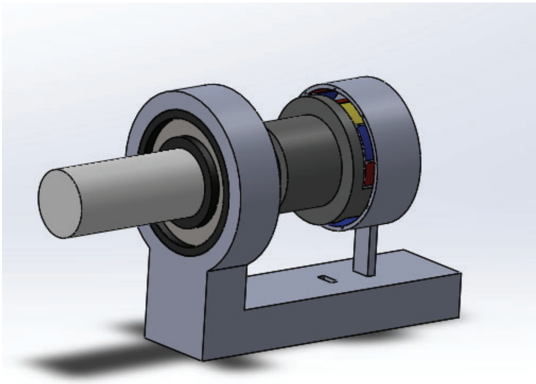
5

Prototyping

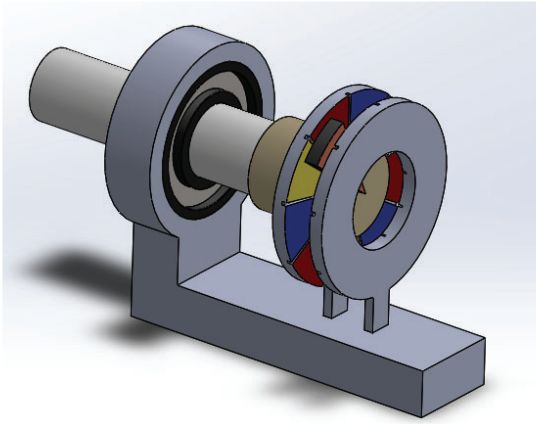
In the prototyping chapter the physical prototypes of the different sub-solutions are shown and the working process of the prototyping explained. Some complex sub-solutions are further divided to facilitate the iterative prototyping process. The chapter ends with some conclusions and knowledge gained from the prototyping of the product and sub-solutions. If the reader is only interested in the final prototype for the encoder unit this is presented in chapter 7.1, Results.

5.1 Sensor prototyping

In order to test the sensor technology of the different concepts simple models were created, mainly through 3D-printing and building circuits on veroboards using basic electrical components. These proof of concept prototypes were used to test the different sensor technologies. Figures 5.1 and 5.2 show 3D-models of the different setups modelled using Computer aided drawing (CAD). The base of the test-rig, the ball bearing and the shaft were the same for every setup while the other parts differed depending on sensor type and implementation. The performance of the prototypes were tested and evaluated to determine if any of the sensor types or implementations could be eliminated in this stage. Both the electrical functionality and the physical properties of the prototypes were evaluated.

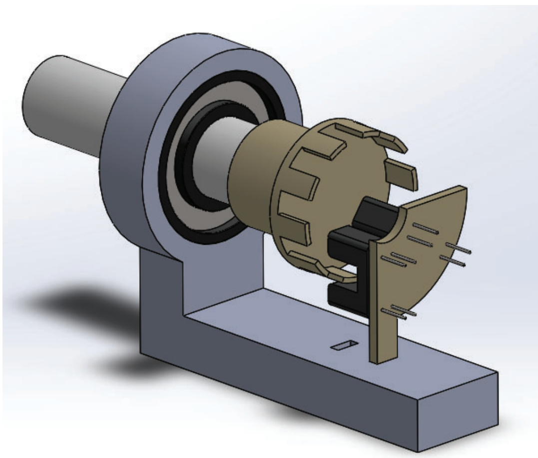


(a)

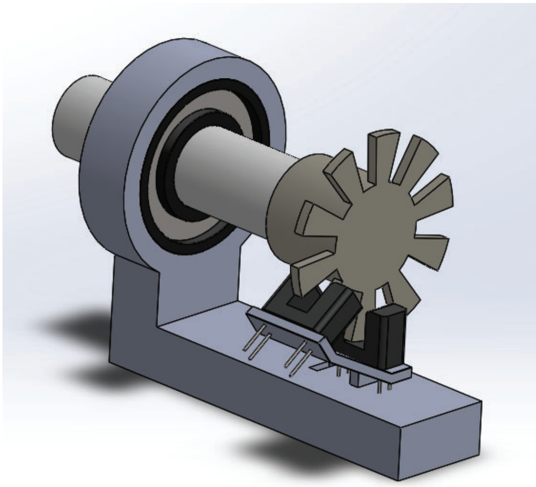


(b)

Figure 5.1 The two versions of the test rig with capacitive sensors, one with cylindrical rotor and stators (a) and one with flat rotor and stators (b)



(a)



(b)

Figure 5.2 The two versions of the test rig with optical sensors, one with cylindrical "teeth", a forked wheel, (a) and one with radial "teeth" (b)

The electrical properties were tested by creating simple circuits to achieve the wanted characteristics to see if the sensors could give a readable output signal.

Capacitive sensors. The first prototypes of the capacitive encoders were created using copper tape as the stator plates and a plastic rotor as the dielectric material that moved between the stator plates, changing the capacitance in accordance with how much of the stator plates the rotor was covering. The designs had 9 sections on the stator plates, where every third one was parallel-coupled to reduce the amount of measurement points required. By measuring the change in capacitance over the different sections, i.e. which section was covered, and in which order the change happened the direction of rotation and rotational speed could be determined. The number of sections determined the resolution of the encoder, with 9 sections per stator plate there were 9 pulses per revolution (PPR) which was enough for the intended application although in the lower span of what could be accepted. In addition to the physical part of the encoder, a circuit to read the results was built. The circuit can be seen in Figure 5.3 and uses a 555 timer to produce readable outputs for an oscilloscope. The signal was read by analyzing the time that the signal was high for each period. A higher capacitance, that is when the rotor was between the measured sections, would lead to the output signal of the oscillator being high for longer than with a lower capacitance.

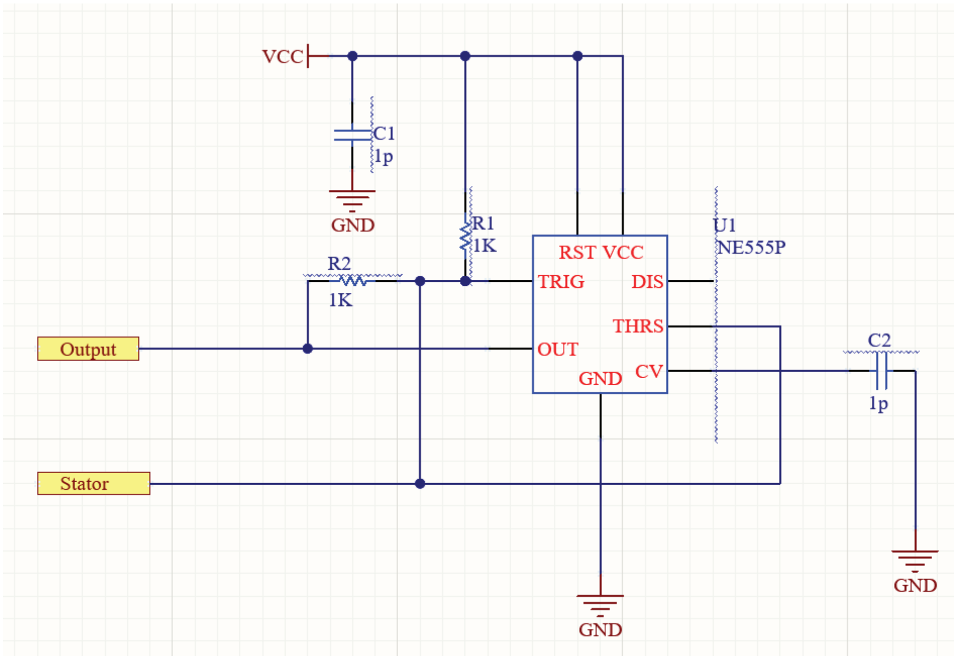
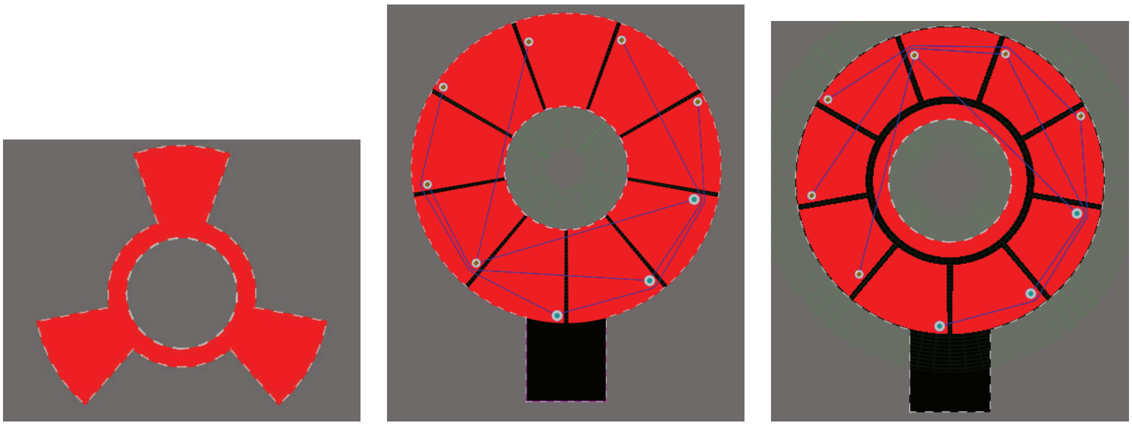


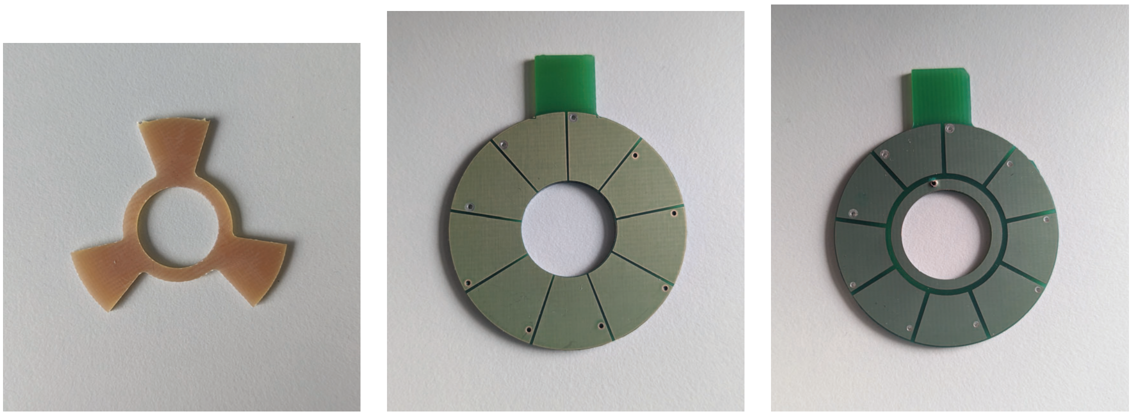
Figure 5.3 Test circuit for capacitive encoder

When building the first iteration of the capacitive encoder prototypes, using copper tape and 3D-printed parts, the capacitance measured was deemed too low to produce a reliable measurement, due to requiring a very small distance between the stator plates and getting a lot of disturbances in the circuits from hand soldering and using veroboards which produce parasitic capacitances. Thus the decision was made to design and order PCBs to see if they would produce better results. Using PCBs would reduce the disturbances from the circuit while also allowing for higher precision of stator plate placement and a shorter distance between the stators. For the PCB prototypes, two different setups were designed and tested. One had the same basic layout as the original prototype, hereafter referred to as the dual-stator design, which would work in the same manner. The other one was an adaptation of the structure described by Hou et al. which would only require one stator plate and a rotor, instead of two stator plates and a rotor [Hou et al., 2017]. This setup is hereafter referred to as the single stator design. This design could prove beneficial, since it would drastically simplify the assembly of the encoder, as well as allow for even shorter distances between the plates, further increasing the capacitance levels. In this step of the process the capacitive encoder with cylindrical parts seen in Figure 5.1a was eliminated, due to the increased cost of producing cylindrical PCBs compared to regular ones. This would highly increase the price of the unit while not giving a lot of upsides and since one goal of the project was to develop a cost effective encoder it was considered a suboptimal solution. The PCB designs can be found in Figures 5.4. The same rotor was used for both designs. The actual printed PCBs can also be found in Figures 5.5.



(a) **(b)** **(c)**

Figure 5.4 PCB designs where the red areas are copper plated, the gray pins are connectors to the bottom layer and the blue lines are copper lines that connect pins. Seen in are the prototype designs of the rotor (a), the dual stator plate (b) and the single stator plate (c)



(a) **(b)** **(c)**

Figure 5.5 Printed PCBs of capacitive encoder prototypes, seen are the rotor (a), the dual stator (b) and the single stator (c)

Both prototypes were tested using the 555-circuit, analyzing if they could output a reliable signal that could be used in the encoder. The prototype with only one

stator could not provide a reliable signal strong enough to be used. For this reason the single-stator solution was disregarded in further testing, which is further discussed in section 7.2.2 Prototyping.
The prototype with 2 stators however yielded a rather stable signal with an approximate change in capacitance of 10 percent of the base value when compared to being completely covered by the rotor. This along with comparators, amplifiers and filters could be a feasible setup for the final encoder.

Optical sensors. The first optical encoder prototypes were built using two fork coupler photo interrupters and our 3D-printed test rig. To measure the direction and speed of rotation the photo interrupters were placed with an angular difference of one and a half pulse, ie. one and a half tooth on the forked disc. This meant that depending on which photo interrupter got activated/deactivated first and how long the pulses were the direction and speed of rotation could be determined. The rotor plates had 10 "teeth" with an angular width of 18° each, thus resulting in a 54° angular difference between the photo interrupters. This setup gives a resolution of 40 PPR giving quite a bit higher resolution than the capacitive setup. When testing this a simple circuit for visual feedback was created and can be seen in Figure 5.6.

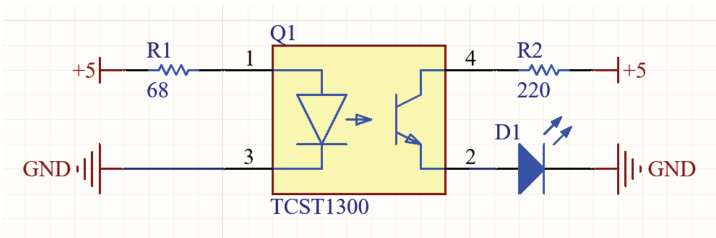


Figure 5.6 Test circuit for optical encoder

Mechanical sensors. For proof of concept a simple conductive incremental encoder that had been used in a previous project was used. It was disassembled to make sure it worked in a similar way to the proposed mechanical encoder solution and when that had been confirmed the encoder was reassembled. Since the mechanical encoder relies on physical connections and simply conducting the signal it did not require any advanced circuits for testing. In a similar way to the optical encoder the mechanical encoder can read rotational speed and direction of rotation by having two electrical connections with a positional difference of one and a half phase. By observing which connection was conducting first, the direction of rotation could be determined.

5.2 Shaft prototyping

A first rendition of the shaft was 3D-printed to get a basic idea of how the shaft would fit into the housing as well as getting a feel for how the housing could be assembled. Later a more refined version of the shaft was designed as seen in Figure

5.7 with geometry and dimensions adapted to fit the already existing forked wheel available at ASSA ABLOY. The 3D-printed shaft prototype with the final design can be seen in Figure 5.8.

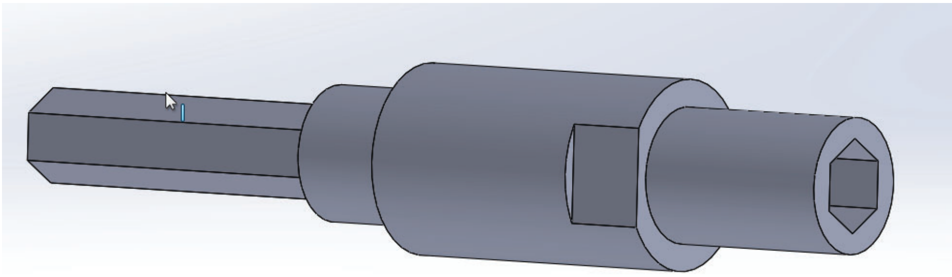


Figure 5.7 CAD model of the final design of the shaft

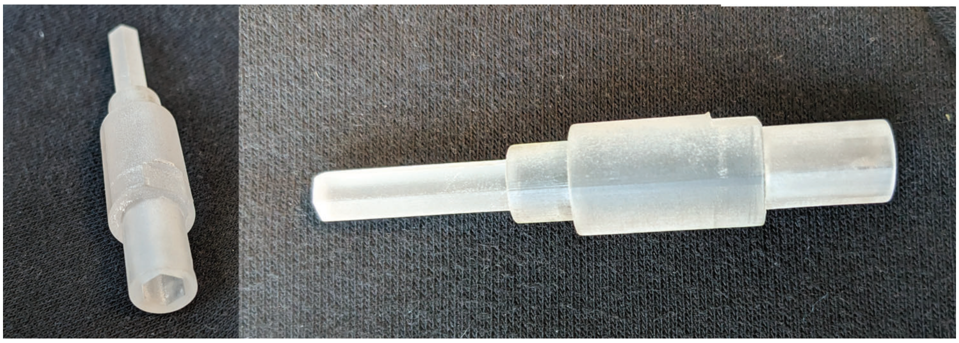


Figure 5.8 The final shaft design, printed in plastic seen from two angles

The final version of the shaft was to be made of metal, however, the plastic version was enough to put together a working prototype of the encoder unit. There were some concerns regarding the fit and seal between the shaft and bearing when using the plastic shaft, but with the bearings and rotational seal taking longer than expected to get specifications for and to order it was decided that this consideration would have to wait until the specifications of the final bearings were set, thus it is not included in this report but mentioned for future work.

5.3 Housing prototyping

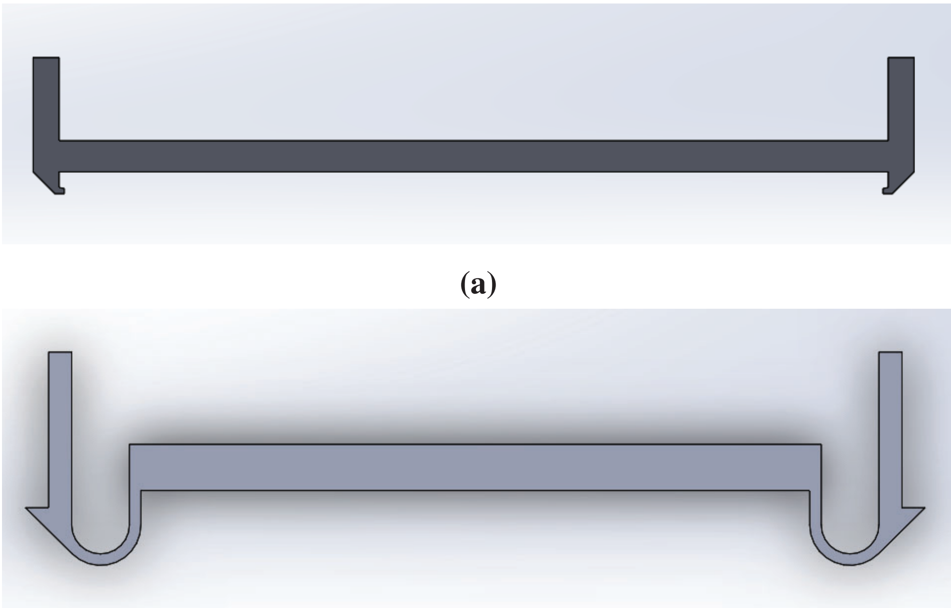
The prototyping of the housing consisted of multiple parts and problems to solve. The solutions for these problems were prototyped individually to facilitate the iterative process, making each prototype easier to build and faster to make changes to. The sub-parts prototyped were the following:

- Connection between the housing base plate and motor
- Connection & seal between the housing base plate and main housing

- Output cables from the housing
- Safety stop for manual drive & safety cover
- Shaft attachment & radial seal

5.3.1 Connection between the housing base plate and motor

The main idea for the connection between the housing base plate and motor was a click or snap on solution to make the mounting and removal of the encoder to the motor as easy as possible. Two variations of connectors were 3D-printed, one connecting on the inner edges and one on the outer edges of the metal grid of the motor cover. These were tested to find out what solution would perform the best. Both solutions would fasten to the motor without issue but the version connecting on the outer edge was very hard to remove after it had been connected and it was opted to use the solution that would fasten on the inner edge of the metal grid instead. Both solutions had "arms" to squeeze when removing the connector from the motor. Cross sections of the solutions can be seen in Figure 5.9.

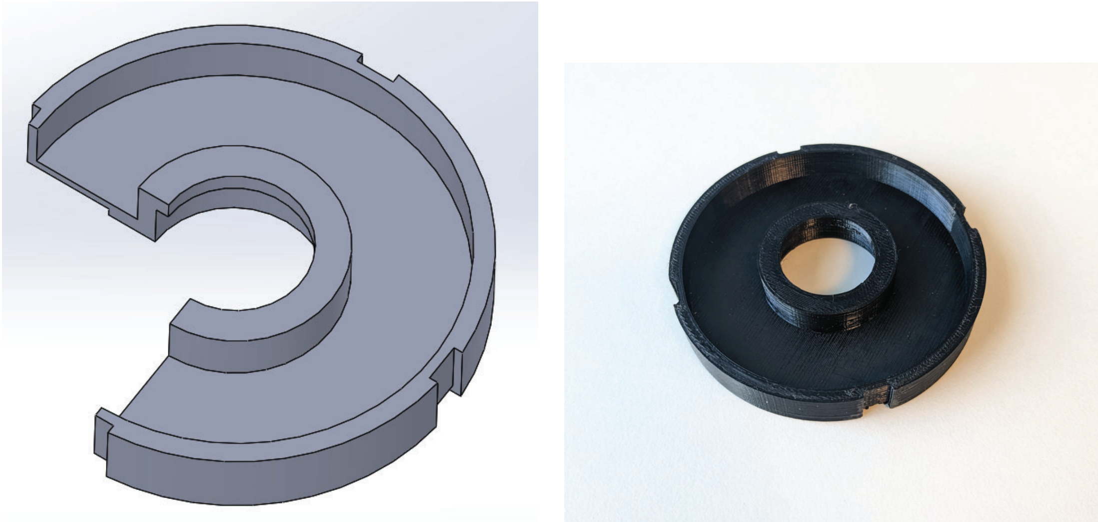


(a)

(b)

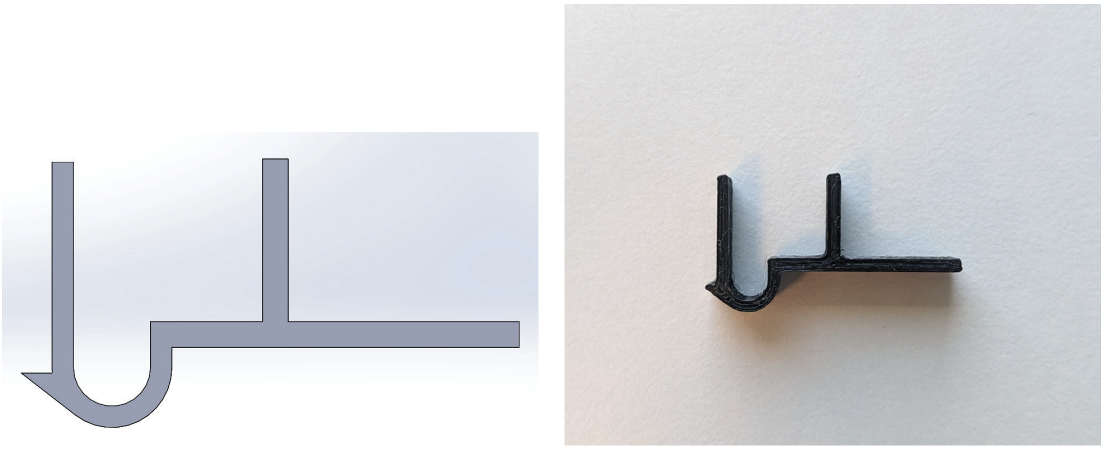
Figure 5.9 The two connector prototypes, the one fastening on the outer edge (a) and the one fastening to the inner edge (b) of the metal grid of the motor end cap

When testing this solution in conjunction with the base plate it was not possible to print them as a single piece because of limitations in 3D-printing. The snap-on connectors were designed as separate parts from the base for this reason. The mounts were made into four separate parts that would be glued into grooves on the housing base seen in Figure 5.10. Both the design and physical prototypes of the mounts can be seen in 5.11.



(a) **(b)**

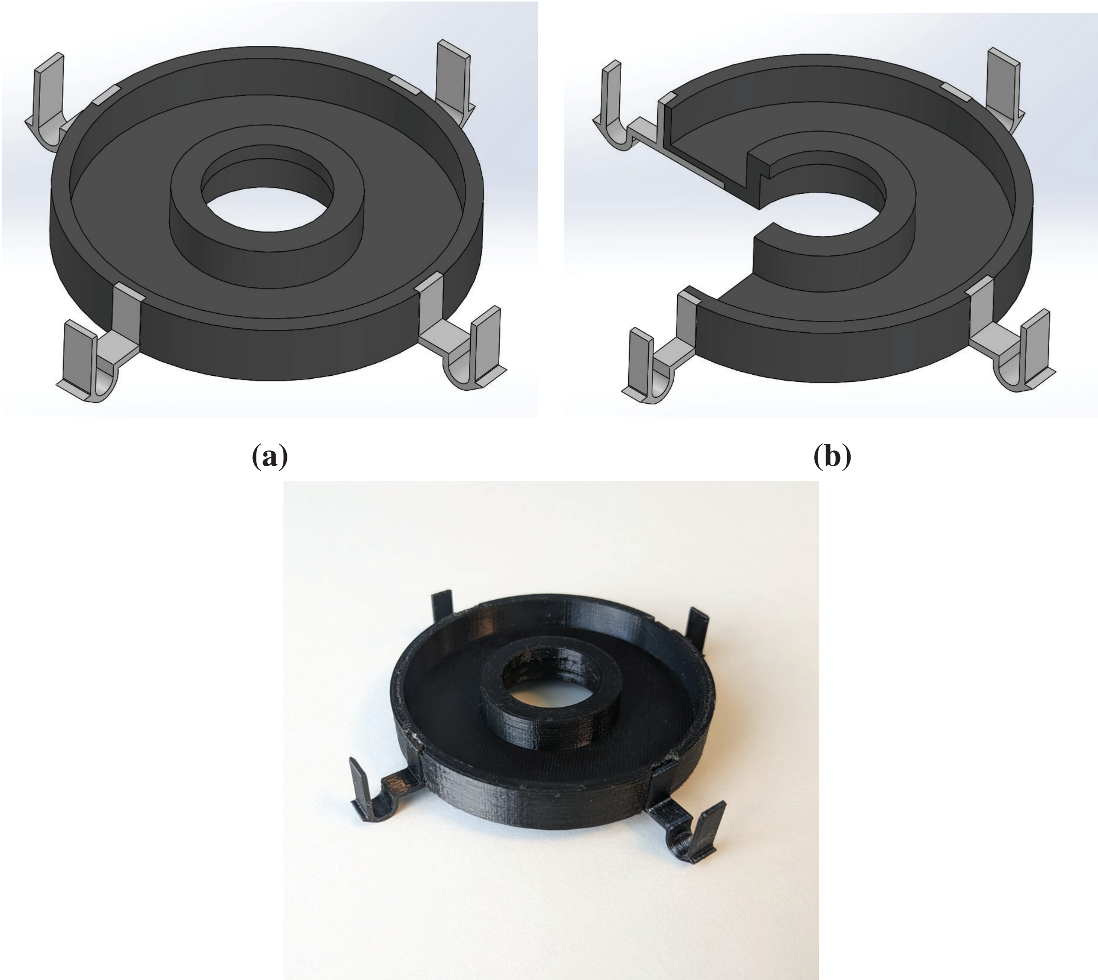
Figure 5.10 CAD model (a) and physical prototype (b) of the base plate with grooves for snap on mounts. A quarter of the CAD model is hidden to display the cross-section of the grooves.



(a) **(b)**

Figure 5.11 CAD model (a) and physical prototype (b) of the separated snap-on mounts

In the final prototype this separated solution would not be needed since the base with connectors could be injection molded as a single part without issue. The CAD assembly and physical prototype of the separated connectors glued together with the housing base can be seen in Figure 5.12



(a) (b)

(c)

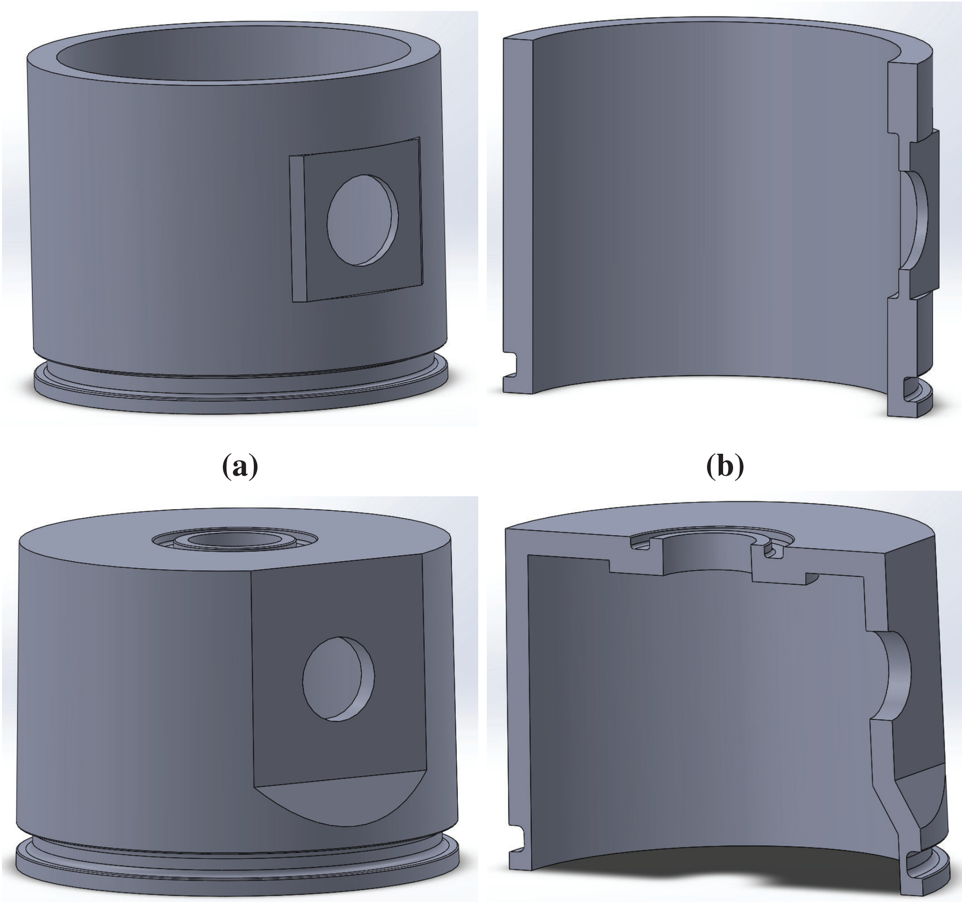
Figure 5.12 The assembled base plate with snap-on connectors, two CAD models (a) & (b) with one having a quarter hidden to display the snap-on mount position as well as the physical model (c)

5.3.2 Connection & seal between the housing base plate and main housing

A prototype of the main housing for testing the connection between the base plate and main housing was 3D-printed. For sealing it had a groove for an O-ring according to standard ISO-3601/1. The first prototype also had arms similar to the snap-on connectors for the motor to hold the base and main housing together. When the prototype was made a problem arose with the printed connectors breaking very easily when strained due to 3D-printing being in layers and the forces applied were along these layers. A solution was to print the connectors separately in a similar fashion to the arms of the connector to the housing. However, it was also noticed that the seal between the O-ring and housing was tight enough so that no other connection was needed to hold the housing and base together. There were some concerns whether this was due to the small ridges that are an artefact of 3D-printing increasing the friction and making the friction fit work so well. It was decided to use this friction fit solution either way and if needed to add ridges or an inner score to the base plate to make sure the connection would give an even better fit. The seal for this prototype was made using O-rings available at ASSA ABLOY while the final solution would need larger O-rings due to the larger diameter required of the housing. The prototype showed that the solution would work and the seal using the larger rings could be trusted since that solution would also be according to ISO-3601/1.

5.3.3 Output cables from the housing

The output cables from the housing were needed to output the correct signals to the control cabinet as well as give input voltage and ground to the electronics within the housing. This would also need to be tightly sealed from the outside environment to ensure that the IP rating was fulfilled. To do this a cable gland was used and to fasten it a version of the housing was printed with a flat area with a through hole on the side where the cable gland would fasten. The flat side was slightly set into the cylindrical housing to make sure the thickness of the flat part was thin enough for the cable gland to connect securely on both sides. After the first iteration, with a flat inset, it was decided to make the whole side flat instead. This was due to production concerns since the inset would not have been possible to injection mold. A comparison of the versions can be seen in Figure 5.13 The bottom was kept cylindrical to be able to keep the radial seal using an O-ring. The cable gland had a rubber seal to keep tight around the through hole where it was inserted as well as a rubber seal around the cables which could be tightened to ensure a proper seal.

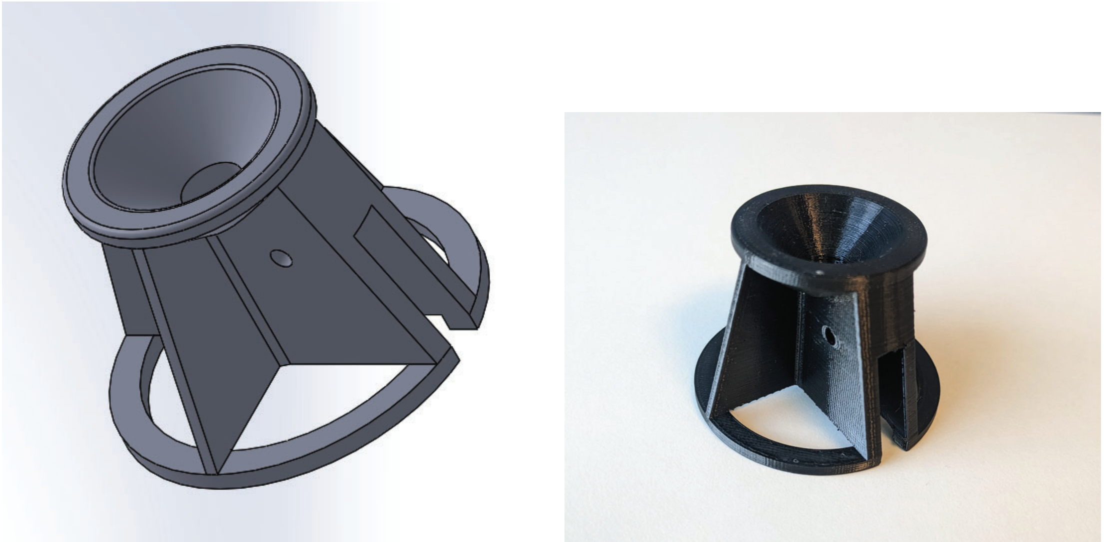


(a) **(b)** **(c)** **(d)**

Figure 5.13 The two housing prototypes, one with a flat area set into the cylinder (a) & (b) and one with a complete flat side (c) & (d), for connecting the cable gland along with cross-sections of them both

5.3.4 Safety stop for manual drive & safety cover

With the requirement of being able to manually drive the motor, a hexagonal hole on one end of the shaft was included. Since there is a risk of injury or damage if the motor starts running when the manual crank is inserted, a safety solution was required. Both a housing for a micro switch and an opening with a sealing lid were prototyped. The housing for the micro switch can be seen in Figure 5.14. The housing for the micro switch would have a hole guiding the manual crank making sure the switch was clicked before connecting the crank to the shaft in the encoder and it would be attached to the encoder housing according to Figure 5.15. After prototyping this was deemed more complicated, as well as bulkier than the alternative using a lid and sensor to notice when the lid was open. An additional problem with this solution was that it would require an additional opening for cables into the main housing.



(a) (b)

Figure 5.14 CAD model (a) and physical prototype (b) of the micro-switch holder and crank guide for shaft detection

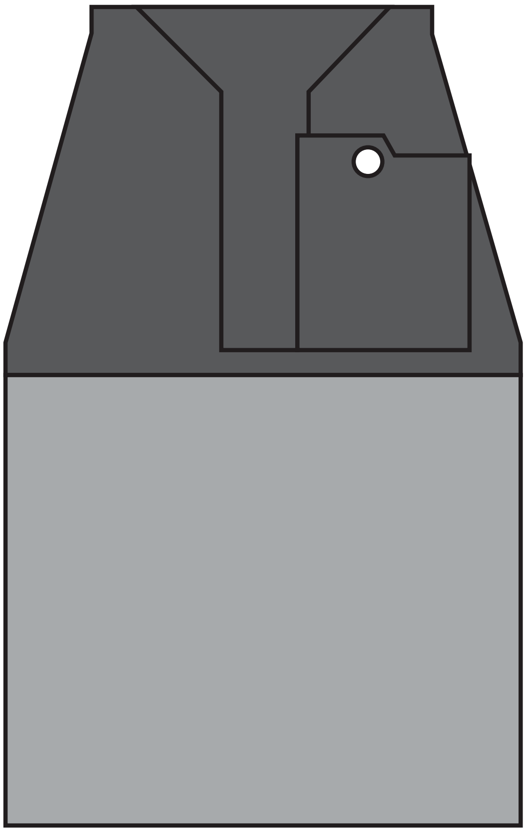
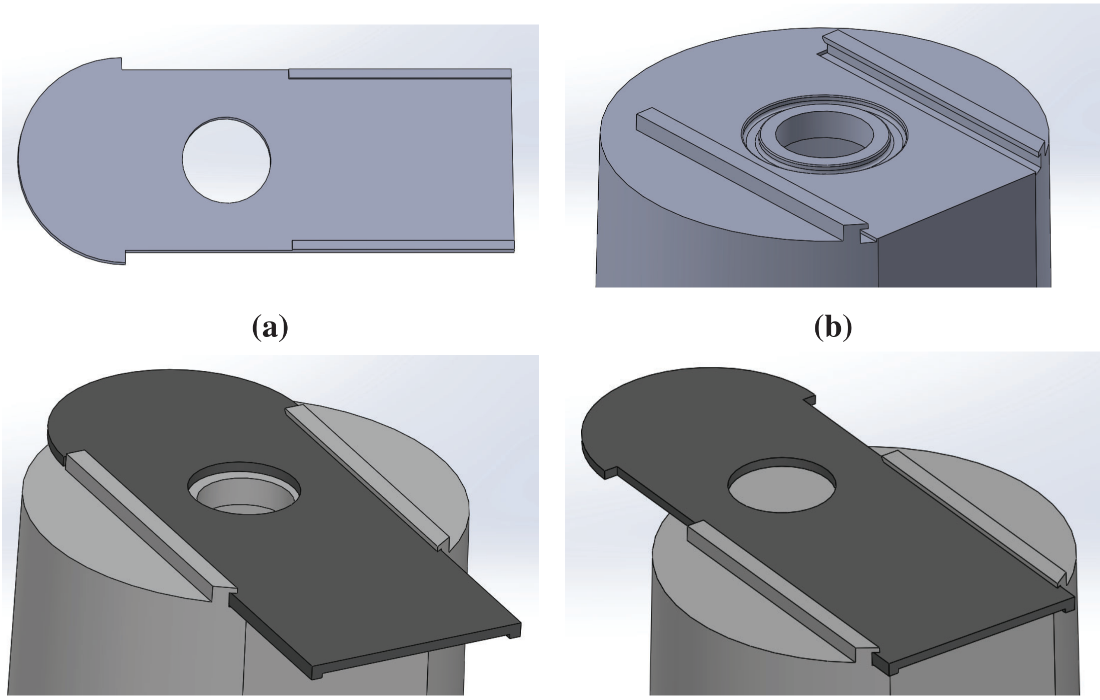


Figure 5.15 A schematic assembly of the micro switch holder (dark grey) attached to the end of the encoder housing (light gray)

The sliding lid was designed as seen in Figure 5.16 and was made to lock in place after being inserted into its slot the first time, so it would not come off during use, or go missing when opened. There would be an accompanying sensor to notice when the lid was in the open position and this sensor was also prototyped and tested making sure the solution worked. A low cost sensor was added to the main PCB of the encoder to work with the lid.

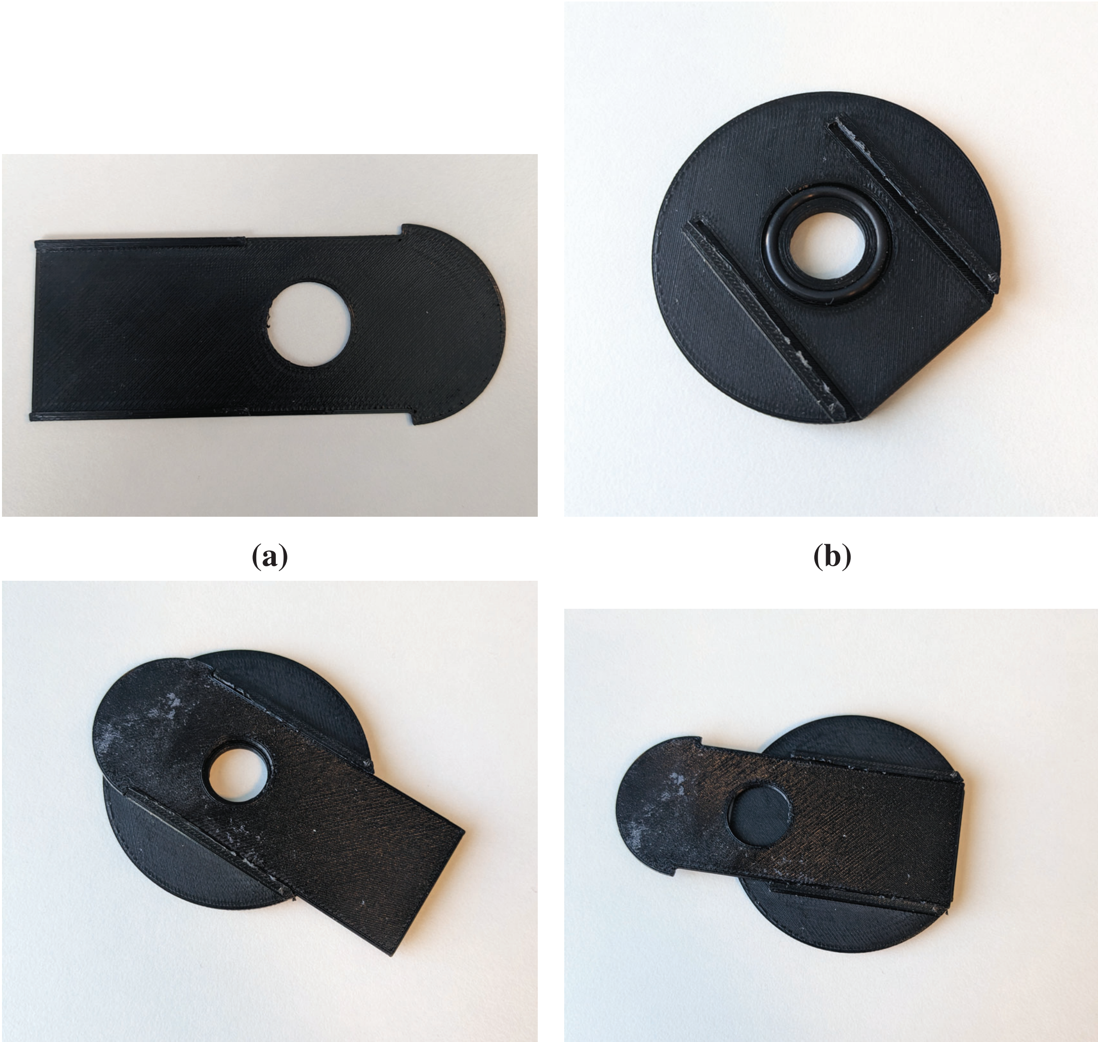


(a) (b)

(c) (d)

Figure 5.16 CAD models of the lid for safety stop and sealing. Both the separate parts; the lid (a) and the housing with rails (b) as well as the parts assembled in the open (c) and the closed position (d) are shown.

There were some problems when prototyping the lid as a part of the main housing because of the use of a 3D-printer, however the solutions were continuously discussed with engineers on ASSA ABLOY to make sure the parts could be produced through injection molding in the actual product. In practice for the prototyping this meant the prototypes for the top lid were printed in separate parts and glued to the main housing rather than molded as part of the main housing. There was also an O-ring seal added according to ISO-3601/1 sealing the opening when the lid was in the closed position to keep the housing safe from contaminants and water when not being run manually. While dust could come in during manual operation of the motor, this is done so seldom that it was deemed a non issue when discussed. The prototype of the top lid can be seen in Figure 5.17



(a) (b) (c) (d)

Figure 5.17 Physical 3D-printed parts of the lid for safety stop and sealing. Both the separate parts; the lid (a) and the housing with rails (b) as well as the parts assembled in the open (c) and the closed position (d) are shown.

5.3.5 Shaft attachment & radial seal

The first prototype used a large ball bearing that was readily available from the start of the project and the main function of this was to see the encoder in motion rather than having a proper seal and dimensions of the final prototype and product. After this a simple plain bearing was 3d-printed and tested. Some big upsides were the simplicity of assembly, with just needing to push the bearing in place on the shaft and housing, as well as the low price with it simply being a solid plastic piece. However, when tested it was quickly established that to fulfill the required level of water and dust protection, the friction when rotating would be too high and could thus disturb motor functionality. With such high friction it could also become a problem of wear and tear, since the encoder should survive a high number of rotations.

After this a ball bearing with dimensions according to the final shaft prototype was used, however no radial seal was used. The bearing was simply friction fitted into the housing and the shaft was also friction fitted into the bearing. This was done to have a functioning prototype but did not ensure a proper seal. There was a discussion with a supplying company for ASSA ABLOY that would come up with a final solution for the bearing and sealing solution, however this solution was not finished within the scope of the thesis work and was thus left to future work. The housing and shaft was designed with standard measurements of bearings in mind and as such it would be easy to change the bearing in the future to the one supplied by the external company, and make small adjustments to dimensions of the housing and shaft if needed.

5.4 Conclusions from prototyping

From the different steps and areas of prototyping a couple of conclusions could be made. Regarding the sensor technologies both the mechanical and capacitive were deemed unsuitable for the final solution. The mechanical connection would work rather well in most regards, for example that it would provide a reliable signal and the production cost would be quite low. However, with the high amount of rotations that the encoder would have to endure, it would most likely cause significant wear with a mechanical connection, as well as not working reliably at high speed, thus making it unsuitable for the motor encoder.
The capacitive encoders also had some positive aspects, such as a relatively low production cost, a high durability and resistance to disturbances and high theoretical resistance to dust and water. However, when tested, the signals proved too weak or unreliable to provide a reliable solution, which is further discussed in the chapter 7. Discussion .
The optical encoders were kept for further development due to their high reliability and good performance in testing. They were also a low cost solution thanks to affordable components and low requirements for additional components on the electrical circuit to provide the wanted type of signal.
The shaft was determined to have an 6mm hexagonal hole on one end and a 6mm hexagonal shaft on the other end, the rest of the aspects were determined in regard to the rest of the encoder. The material was decided by the required strength and surface tolerances, the outer diameter dimension would be determined by bearing as well as radial seal dimensions and the shaft length was determined by how long the encoder would have to be due to the dimensions of other parts and avoiding interference with these.
The housing was tested in separate parts and brought together in a combined final prototype which can be read about in chapter 7.1. Results. The main parts of the housing was decided to be a cylinder with one end completely open while the other end would have a small hole and rails for the lid on the outside. On the side of the

cylinder one side would be flat in order to attach a cable gland in a water- and dust-proof manner. The flat side would also have a hole that the cables and cable gland would go through. The flat side along with a rail on the inside of the cylinder wall would also work as guidance for the PCB placement and orientation. On the open end of the cylinder an end cap would be attached with the help of an o-ring in a groove on the outside of the cylinder. The O-ring would seal the housing as well as fasten the two pieces together through friction. This cap would have a radial bearing and a radial seal fitted into it to which the shaft would be attached. The cap would also have snap-on connectors to attach the encoder to the motor housing.
The output cables from the PCB were determined to have the same exit and to be grouped in a singular cable to only require one protection seal from water and dust. Regarding the seal a solution of using a cable gland was chosen due to its ease of assembly as well as a low cost in comparison with producing a completely new solution.
The safety feature of not having the motor run while manually operating the motor was decided to be a slide-lid with a sensor which detects if the lid is open or closed. This also solved the issue of sealing the bottom of the encoder from water and dust, since an o-ring was added under the slide-lid which sealed the entry to the encoder housing.
The shaft was decided to attach to the housing through friction fitting to a bearing connected to the housing. This would allow for the shaft to rotate while still holding it in place.

6

Detail design

The detail design of the encoder was done after the prototyping step, where all the winning concepts were refined, tested and combined to provide a final solution. Each separate part of the encoder was refined separately as well as together with its connecting parts and the motor. In the detail design final dimensions were set and coordinated between the different parts of the encoder. The Detail design was done in the following sub-division:

- Sensors, electronics and PCB
- Base cap and mounting to motor
- Main housing
- Shaft
- Safety stop for manual drive

The design of the final prototype can be seen in Figure 6.1 with all of its components separated in an exploded view. The detail design of the components is presented separately.

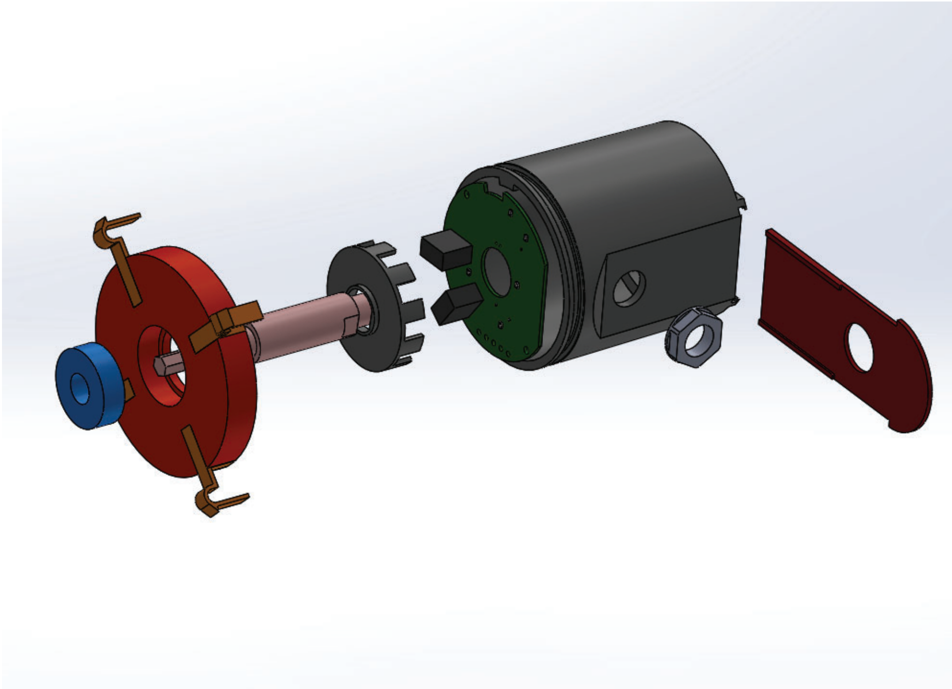


Figure 6.1 Exploded view of the encoder CAD model

6.1 Sensors, electronics and PCB

After testing and prototyping it was decided that the best solution for a low cost, reliable encoder would be one utilising optical sensors. When designing the PCB with optical sensors for the encoder there was one main concern, the size of the forked wheel available at ASSA ABLOY. It would be a big economical and logistical advantage to use this same design of the forked wheel for this encoder since it would require no new tools or storage since it is already being used in other motors. This set a requirement for the size of the PCB for the optical sensors to align with the forked wheel. The PCB was designed with this in mind. In regard to the electronics there were no hard limitations, the goal was to make a low cost solution that was compatible with the current system. Because of this, easily available and affordable components were used when possible while also trying to keep the circuit simple and analog.

6.2 Base cap and mounting to motor

The motor-side lid had three main considerations, that it should hold a radial bearing and seal, that it should attach the encoder housing to the motor and be attached to the encoder housing in a water- and dustproof manner. After prototyping and testing the solutions for connecting to the motor the best solution found was the click-on mounts which allow for easy mounting and removal of the encoder base. For the sealing and connection to the main housing the solution was a groove for an O-ring on the outside of the main housing. Some different sizes were tested and the final one was decided based on the size of the main housing, which had a minimum size limitation in order to fit all the other components. The radial bearing that was used for the final prototype was a 10mm inner diameter ball bearing. This could end up changing in the future for the final product but worked well enough for the prototype and is also a common size for bearings meaning it is likely the final solution would have the same size of bearing, although possibly of different model or make. No radial seal was attached for the prototype as this would be decided based on the final bearing used. This bearing and seal solution would be decided with the help of a supplier of ASSA ABLOY specialising in bearings and seals. The bearing was friction fitted into a hole in the housing, from the outside, with a stop to keep the bearing in the correct position. These solutions in combination can be seen in Figure 6.2. The O-ring is simply laid into the base cap for the sake of visibility in the image. In reality it would be set onto and covered by the main housing.

Figure 6.2 The base cap with its ball bearing, snap on connectors and an O-ring for sealing. The O-ring is simply laid in the base cap for the sake of visibility

6.3 Main housing

The main housing consisted of a combination of several parts of the prototyping process and thus all of the parts needed to be kept in mind while doing the detailed design. The minimal possible inner radius was determined with the limiting factor being that the PCB with the forked optical sensors should fit while properly interacting with the forked wheel already available at ASSA. The length was then decided by determining how long of a distance would be required for the PCB, rotor wheel, cable gland and cables to fit without collisions and interference. A flat surface with a hole was added to one side of the cylinder in order to allow for proper mounting of the cable gland. To ensure proper positioning of the PCB inside the encoder, a heel was added for it to rest on, along with two screw holes to fasten it. A rail was also added to the inside to ensure that the PCB had correct orientation of the sensors. On the outside of the housing a groove was added to hold the o-ring for the attachment of the end cap on the motor side.
On the other end of the cylinder the solution for manual drive safety using a slide-lid was included in the same part as the main house to ease assembly. That was done by simply having a flat surface with a groove for the o-ring as well as grooves for the slide-lid to be attached.

6.4 Shaft

The shaft had a couple of set dimensions that were kept the same due to properties of the system; the 6mm hexagonal shaft to be inserted into the motor and the 6mm hexagonal hole to insert the manual drive shaft into, as well as the dimensions for the attachment of the forked wheel. The other dimensions were established to fit the housing and bearing. On the motor side the shaft diameter was set to 10mm to fit the bearing. A flat surface and a lip was added, as a stop when pushing the shaft into the bearing, to hold the rotor in the correct position for interaction with the optical sensors. The rest of the length was determined to properly fit the housing length without causing collisions. To confirm that the shaft would endure the expected forces present during use, simulations of the CAD models were done. These simulations and the results are presented in Appendix C.1.

6.5 Safety stop & manual drive

The safety stop solution used was a sensor connected to the sliding lid, noticing when the lid was open for manual drive. This would also protect anything from coming in contact with rotating parts, if the lid would open unexpectedly. When the lid was open a signal would be sent to stop the motor from running. The dimensions of the hole for the manual crank were set to have clearance for the crank shaft while still guiding it into the hole of the encoder shaft to avoid hitting the PCB and inner components of the encoder. The lid itself was dimensioned in a way that it could be initially fit into the grooves for sliding, but then clicking into place so that it could not easily be removed from the housing. The lid was made thick enough where it would not bend outward, making sure it kept a tight seal over the hole when closed.

6.6 Bill of materials

A bill of materials was created to display an overview of all the parts needed for production of the encoder and the sourcing or production method for each part can be found in Table 6.1

Table 6.1: Bill of materials

Part	Sourcing	Amount
PCB	External supplier	1
Housing	Injection molding	1
Attachment lid	Injection molding	1
Bearing	External supplier	1
Shaft	Turning and milling	1
Slide lid	Injection molding	1
M2 screw	External supplier	2
Cable gland	External supplier	1
Electric cables	External supplier	5
Rotor	Injection molding	1
O-ring	External supplier	2

7

Results & discussion

In this chapter the results as well as discussions regarding methodology, prototyping, results, future work, project evaluation and conclusions are presented. The results of the thesis are in regards to the goals specified in section 1.2.

7.1 Results

A final prototype was developed, compatible with all motors of the high speed doors as well as the control system. In addition to this, key components could be re-used from other ASSA ABLOY products reducing price and complexity of logistics. The final physical prototype connected to the motor cover can be seen in Figure 7.1 and an exploded view of the final prototype 3D model can be seen in Figure 7.2 The final prototype had the same resolution and signal types as other motor encoders used at ASSA ABLOY meaning it will be easy to integrate with their control systems. It is also compatible with all sizes of motors used for the high speed doors making it versatile and easily compatible with the whole system. The production of the encoder, while not tested in full scale, was deemed to be producible at scale and the assembly was easy with relatively few components even in the prototype stage. Although no final cost for the encoder has been calculated due to uncertainties of many of the production costs, a rough estimation showed that this solution cost significantly less than the current solution and within the cost range specified during benchmarking of products with similar capabilities that are available on the market. The temperature, dust and water resistance were not tested for the prototype. This should be done when all final parts have been sourced.

Figure 7.1 The final prototype connected to the motor cover.

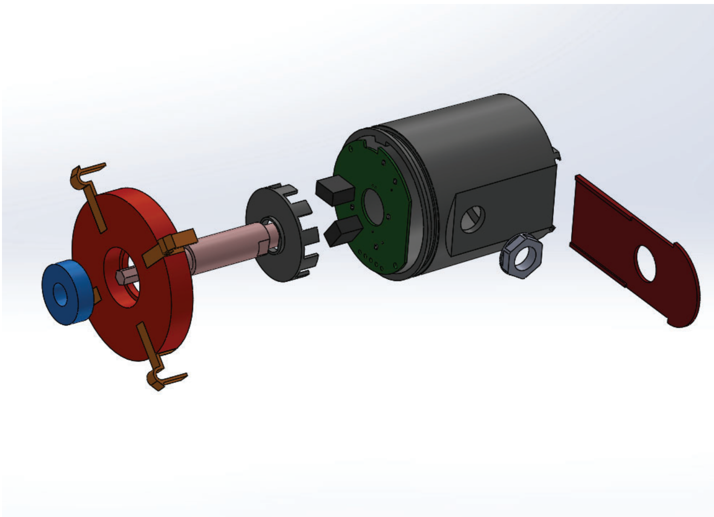


Figure 7.2 Exploded view of the encoder CAD model

7.2 Discussion

The discussion is divided and presented in regards to the different processes and topics of the thesis. These discussions are presented in the following sections.

7.2.1 Methodology

Throughout the development of the encoder, following the Ulrich and Eppinger methodology proved useful in large parts thanks to dividing the process into smaller parts making the project easier to handle, as well as making for a thorough investigation of possible solutions. By following the methodology the authors had a clear starting point and path to follow in the development process. In hindsight however, some steps in the process could have been performed more effectively such as dividing the fastening method and sensor solutions into different concept development steps from the beginning, instead of generating the 32 different solutions, to then continue with a separate concept development step for the fastening solution.

One issue with the intended methodology of the project was the fact that all assumptions made during the start of the project were not true. When the schematics for the motor at hand were made available to the authors it was noted that the encoder would have to connect in a different way than originally assumed and parts of the concept generation had been a waste leading to the need for more concept generation with a base in the half-completed concepts. In the end it led to a good solution but with unnecessary extra steps. During the prototyping process new ideas for solutions were come up with and many times these were the ones that would end up in the final solution and prototype. While it is believed that this ended up generating a better final product it made the process to get to the product less coherent and linear, making it harder to record the process in a coherent way and also had the authors digress slightly from the initial product development plan. For this reason the report has not always been written in chronological order but rather dividing it by the steps taken such as concept generation and prototyping, even if these processes sometimes happened simultaneously and in an iterative manner.

7.2.2 Prototyping

Building the first simpler prototypes was very useful to get an idea of how the different solutions would work, and what issues could arise for each respective solution. This made it easier to narrow down the selection of solutions in an early stage.

A big asset during the prototyping part of the project was the 3D-printers available on site. By making CAD models of the prototypes and 3D-printing them, a lot of ideas could be tested quickly and the ideas were either kept or scrapped depending on the outcome. Even if some parts that would be possible to produce using injection molding were not feasible for 3D-printing, most prototypes could be built by printing several parts and gluing them together.

The capacitive encoder prototype with a single stator was disregarded after testing the signals without being able to get much of an output. This is most likely due to a couple of factors, first of all the capacitive plates had to be quite small to fit in the encoder leading to small output signals. Secondly, the inner ring which is induced with an electrical charge to produce an electrical field to the rotor is quite narrow, making the capacitance value rather small since it is directly dependant on the size of the plates. The electrical charge produced by this capacitance is then utilized to

achieve an electrical field connected to the outer part of the stator plate. The relative difference in capacitance between the outer and inner parts of the stator is then measured to find when the rotor is in between the plates. However, with stray capacitances from the circuit and the small stator plates the relative difference in capacitance value proved to be too small to reliably measure. The signal to measure the relative capacitance and thus the difference could be amplified with a couple of amplifiers added to the circuits, but to not get too high disturbances every amplifier would require filters which would increase the complexity of the PCB and require multiple additional components. Even with these additions it is hard to predict whether the sensors would produce good enough signals. All of the extra electronic components would also increase the cost of the encoder. Instead the decision was made to keep the prototype with two stators which could actually produce a readable signal until eventually this too was scrapped in favour of the optical sensors.
The optical sensors were chosen for further development mainly due to their reliability, relatively cheap price as well as their compatibility with the systems at ASSA ABLOY. With these benefits the optical sensors proved to be the best choice for the application, with the only real downside being that the encoder would require a better resistance to water and dust, rating IP65 while rating IP54 would be enough for the capacitive technology. This is due to the risk of the optical sensors or led lights getting blocked by dust, thus interrupting the light and giving faulty readings. However, this was considered a worthy trade-off for the reliability and other benefits of the optical sensors since reaching the higher IP-rating is not that much more difficult or expensive than the lower rating.

7.2.3 Discussion of results

The final prototype differed quite a bit compared to the authors expectations, in part because the connection to the motor was different than initially expected. This changed portions of the project that were given from the start and obviously had a large impact on the process and end result.
Because of long lead times and the contact with external suppliers of the final bearings taking longer than expected, these bearings were not delivered in time to be included in the physical prototype. The final metal shaft was also not included due to longer lead times from the supplier. This led to the encoder with it's final components not being tested, with significant differences likely to be seen in regards to IP rating. The final prototypes functionality could not be confirmed regarding dust and seal resistance, which was expected in the beginning of the project to be done. While these tests would be needed for a final product, the prototype is a good proof of concept for the encoder and solution as a whole.
For a significant portion of the encoder development time span a capacitive encoder was considered to be one of the most likely techniques to work well in this application. That was because of its many benefits, such as high resistance to

disturbances, low production cost and a long life-span. However, a combination of factors resulted in the authors deciding to not continue the development of the capacitive encoder. The main reason was the type of signal produced by the encoder. With the capacitive technology the signal produced would be an analog triangular wave since the capacity is relative to the amount of the stators covered by the rotor. This would not be immediately compatible with the current system since the current system is programmed to receive two pulse-trains with only two values in each, either high or low. This could be solved using comparators to set the value to max when reaching above 50% of the max value, and min when below that value. However, this would also be prone to issues occurring due to signal irregularities. If the motor would stop near the limit value a small signal error could make the shift happen, thus signaling to the system that the motor moves, while in reality it was perfectly still. This could be solved using filters and amplifiers to get a stronger and cleaner signal, that would however require far more components and complicated circuit than, for example the optical encoder, which would be in conflict with the goal of creating a low cost encoder. Vibrations could also cause the same issue, since even small vibrations near the switch-level could send signals to the control unit that the motor moved.

It was also discovered that the capacitive encoder would not necessarily cost less than the optical, it would be harder to assemble with more separate parts, as well as giving a lower resolution (given the system would need binary signals). The size of the encoder also posed challenges. With the small dimensions required to fit in the encoder, the stator plates needed to be quite small and could only produce a limited amount of capacitance. All of these issues led to the capacitive solution falling short of the optical one in most aspects. The most notable performance improvement would be that the housing would not need to be as tightly sealed against water and dust, however, this was only theorized and never actually tested in practice.

Mechanical encoders were ruled out quite early because of their physical connection requirement, and therefore wear of the encoder itself. With the amount of rotations an encoder would require this physical wear and tear would make mechanical encoders unsuitable for the high speed door application. Resistive encoders were disregarded simply due to the fact that they are not continuous, but rather have a maximum and minimum value, which is not suitable for measuring a high number of rotations.

Magnetic encoders were disregarded during the concept selection stage, due to their high cost in comparison to for example the optical or capacitive technologies. In addition to being more expensive they do not provide any significant benefits for this application.

One of the major goals of the project was to make the encoder cost-effective in comparison to other applicable products available on the market. As mentioned in the Results chapter this goal was deemed to be fulfilled since an estimation of the cost proved to be significantly lower. In this cost estimation, the production and ordering of components were the main considerations. Other factors that could be considered to affect the cost efficiency is the time of assembly. However, from exploration of the market the authors could not find a single solution that would fulfill the requirements completely, without adding additional components to perform for example manual drive. For this reason the assembly was not considered a part of the analysis, since that would be required for the available solutions as well.

7.2.4 Project evaluation

The project as a whole has worked very well, with division of work being equal overall. There has been a lot of important input and help from supervisors, both at Lunds tekniska högskola (LTH) and at ASSA ABLOY, as well as other people at ASSA ABLOY helping when needed, reducing speed bumps and keeping the project moving forward. Most of the work was done in office by both authors, keeping a dialogue as to not do any double work. This was helpful, both in keeping the project moving forward at a steady pace, but also to avoid uneven distribution of work. Being on site was also helpful considering all the practical work done in the product development and prototyping process. Having access to all the facilities at ASSA ABLOY meant that it was easy to test ideas quickly and evaluate if they were worth spending more time on to refine or if they were to be discarded in favour of more promising ideas or more important work. The original project plan was followed quite well but most processes took longer than anticipated, especially the concept generation and prototyping. This was in part because of underestimation of the time needed, but also not factoring in lead times for components and prototypes. The work on the different parts of the project were also less linear than originally planned, due to new findings about the system and due to finding new solutions that needed further development or concept generation. When waiting for deliveries or 3D-prints the report was written continuously to keep what had been done fresh in mind, as well as avoiding having all of the report writing saved for the last couple of weeks. This was very helpful in the grand scheme of things, even though there was still more time spent on the report during the last stages of the project.

7.2.5 Conclusion

Although there is still work with testing the encoder and planning the production, the proposed solution fulfills the specifications set by the company. By starting with a broad scope and considering multiple solutions to the sub-problems a lot of alternatives were explored to end up with an optimal design, both from the perspective of functionality, and simplicity of use. With little to no adaptation of the current system needed, this prototype is ready for integrated testing on the ASSA ABLOY high speed doors. This along with its lower price than comparable solutions available on the market marks this project as a successful endeavor to find a solution to the proposed problem.

7.2.6 Future work

Before production can be commenced there is some further work to be done, which is presented in this section.

Cost analysis. While a rough estimate of the cost of the product has been made, no in depth cost analysis was made in this project. This would need to be done, as well as a final sourcing of all components, for the final product. The degree of cost analysis that has been done was sufficient to make conclusions about whether the encoder would cost less than comparable products on the market but does not give an exact Figure of cost for the final product.

Classifications. For the future it would be good to test the complete prototype looking more closely at IP rating for dust and water resistance as well as functionality in different temperature ranges. Even if the individual sealing solutions are highly likely to work as intended it is important to test the complete product, making sure that all parts work together as intended and see if there are weak spots not noticed in the prototype stage. As for temperature ranges for the product all components were picked to be in the span required by ASSA ABLOY but, again, this should be tested for the whole product to see if interactions between components of the encoder give rise to unexpected behaviour or wider temperature ranges than expected.

Final components. Because of lead times and the prototyping phase taking longer than expected the final solutions for the shaft and bearing were not delivered in time to be included in the report. These solutions would have to be tested and evaluated when they are made available to evaluate their performance. There are also some factors that could be altered in order to achieve for example faster assembly of the encoder that were not possible with the production methods available during this project. One such thing is that the sealing for the output cables could be integrated in the housing. This would lead to the cables simply needing to be plugged in rather than placing the cables upon assembly and screwing the cable gland in place to squeeze them in order to achieve the required sealing properties.

Production planning. One important thing to be done with the project is the production planning. The scope of this project was to create a working prototype but for the final product a whole production chain needs to be planned and implemented, taking into account how to most effectively produce different parts in large quantities. The prototype looks different than what a final product would look like in large part because the final production methods cannot be feasibly used in a fast and iterative prototyping stage. This would have to be accounted for and carefully planned before any upscale production could take place.

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A

Appendix A: Product development - tables

In this appendix the tables for the product development steps from "Identifying customer needs" to "Benchmarking" are presented. The tables are moved from the chapter where they are referenced in the text for easier readability of the report.

A.1 Product development - tables

Table A.1: Original customer statements and needs

Customer statement	Interpreted need
There is a lot of electrical disturbances in the motor	Resistant to electrical interference
Survive an industrial environment	Resistant to moisture and dust/dirt
——״——	Resistant to a range of temperatures
——״——	Resistant to some vibrations
——״——	Resistant to physical shocks
Lower cost than the current solution	Lower price per unit than similar solutions on the market
Should be placed close to the motor	Can handle magnetic disturbances
——״——	The measurements fit the motor chassi/axis

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Table A.1: Original customer statements and needs (Continued)

Easy to assemble in-house	Does not require advanced assembly operations
——״——	Allows for quick assembly
Scalable production	The components should be easy to supply in high volumes at a reasonable price
It should fit multiple motors	Compatible with ASSA ABLOYs standard motors
——״——	Is mountable on the current motor/axis
Long life-span	The life-span of the encoder should be equal to that of the motor
——״——	It does not require a lot of/any maintenance
Compatible with the control system(signals, outputs)	Transmits signals that are readable to the current control system
Precise enough resolution	The measurements should have the same or better resolution than the current encoder

Table A.2: Grouped customer needs and their relative importance

Need no.	Customer need	Group	Importance 1-5 (5 most important)
1	Resistant to electrical interference	Robustness	5
2	Resistance to dirt and moisture	Robustness	5
3	Resistant to a range of temperatures	Robustness	5
4	No disturbance from vibrations	Robustness	3
5	Resistant to physical shocks	Robustness	2
6	Resistant to magnetic interference	Robustness	4

Continued on next page

Table A.2: Grouped customer needs and their relative importance (Continued)

7	Does not emit electromagnetic interference (EMI)	Robustness	5
8	Lower price per unit than similar available products	Production	5
9	Component supply is scalable	Production	5
10	Quick to assemble/install	In-house and usage	2
11	Does not require advanced assembly/installation techniques	In-house and usage	2
12	Requires little or no maintenance	In-house and usage	2
13	Compatible with ASSA ABLOYs standard motors	Compatibility with system	4
14	Is mountable on the current motor/axis	Compatibility with system	4
15	The life-span of the encoder should be equal to that of the motor	Compatibility with system	3
16	Fits the motor measurements/design	Compatibility with system	1
17	Transmits signals that are readable to the current control system	Compatibility with system	5
18	The measurements should have the same or better resolution than the current encoder	Functionality	5

Table A.3: Customer needs with metrics, their importance and their respective units

Metric no.	Need nos.	Metric	Importance 1-5	Unit
1	1	Electromagnetic compatibility (EMC)	5	-
2	2	IP rating	5	List
3	3	Working temperature	5	°C

Continued on next page

Table A.3: Customer needs with metrics, their importance and their respective units (Continued)

4	4	Vibration	3	G, Hz
5	5	Maximum stress without fracture	2	Ns
6	5	Maximum allowed displacement	2	m
7	5	Impact protection (IK)	2	J
8	6	Magnetic disturbance resistance	4	Tesla[T]
9	7	EMI emission	5	-
10	8	Cost per finished unit	5	SEK
11	9	Number of components available yearly	5	Pcs
12	10	Assembly time per unit	2	s
13	11	Does not require advanced tools/techniques for assembly	2	Subj.
14	12	Years between services	2	Years
15	13	Compatible with current ASSA ABLOY motors	4	Binary
16	14	Mountable on current motor/axis	4	Binary
17	15	Life-span expectancy	3	Years
18	16	Size of mounting side	1	m*m
19	17	Output signals compatible with control system	5	Binary
20	18	Pulses per revolution	5	PPR

Table A.4: Benchmarking values of existing competetive products in the market

Product	AMT 10E3-V	MIR 10	HEDM-5605#J06
Type of encoder	Capacitive	Magnetic	Optical
1. EMC	-	-	-

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Table A.4: Benchmarking values of existing competetive products in the market (Continued)

2. IP rating	Max 95% non condensing humidity	IP66/67 93% relative humidity, condensation permitted	Non-condensing atmosphere
3. Working temperature	-40°C - +100°C	-40 - +85°C	-40°C - +70°C
4. Vibration	10G, 20 500 Hz	30 g, 10-2000 Hz	20 g, 5-1000 Hz
5. Maximum stress without breaking	-	-	-
6. Maximum allowed displacement	-	-	-
7. IK	Shock, 50G, 11 ms	Shock, 500 g, 6 ms	-
8. Magnetic disturbance resistance	May have issues with some stepper motors	-	-
9. EMI emission	-	-	-
10. Cost per finished unit	243 SEK exc. VAT	621 SEK exc. VAT	497 SEK Exc. VAT.
11. Number of components available yearly	n/a	n/a	n/a
12. Assembly time per unit	n/a	n/a	n/a
13. Does not require advanced tools/techniques for assembly	n/a	n/a	n/a
14. Years between services	-	-	-
15. Compatible with current motors at ASSA ABLOY	Probably	Yes(most likely)	Probably not, only has 8.9mm hole

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Table A.4: Benchmarking values of existing competetive products in the market (Continued)

16. Mountable on current motor/axis	Yes, might need mount	Yes, might need mount	Yes, might need mount
17. Life-span expectancy	-	-	-
18. Size of mounting side (Width x Height)	53x43x9mm	54.8x55(15+ 40)mm	52x41x18mm
19. Output signals compatible with control system	Yes	Yes	Yes
20. Pulses per revolution	120-5120 PPR	320-4096PPR	200-256PPR

Table A.5: Benchmarked values for our product

Metric	Worst accepted value	Optimal value	Target value
1. EMC	-	-	-
2. IP rating	IP54	Higher depending on sensor type	IP54
3. Working temperature	-20°C - +60°C	-30 - +70°C	-30°C - +70°C
4. Vibration	-	-	-
5. Maximum stress without breaking	-	-	-
6. Maximum allowed displacement	-	-	-
7. IK	-	-	-
8. Magnetic disturbance resistance	Does not impact measurements significantly	Does not get affected by magnetic disturbances	Does not impact measurements significantly

Continued on next page

Table A.5: Benchmarked values for our product (Continued)

9. EMI emission	Does not affect motor or control system	Does not affect motor or control system	Does not affect motor or control system
10. Cost per finished unit	300 SEK exc. VAT	50 SEK exc. VAT	100 SEK Exc. VAT
11. Number of components available yearly	same as systems produced at ASSA ABLOY	twice the amount of systems produced at ASSA ABLOY	1.5 times the amount of systems produced at ASSA ABLOY
12. Assembly time per unit	5 minutes	30 seconds	1 minute 30 seconds
13. Does not require advanced tools/techniques for assembly	Requires advanced workshop-level tools	Does not require tools	Requires basic tools
14. Years between services	-	-	-
15. Compatible with current motors at ASSA ABLOY	Yes	Yes	Yes
16. Mountable on current motor/axis	Yes, might need mount	Yes, might need mount	Yes, might need mount
17. Life-span expectancy	1 year/500,000 cycles	Same as or greater than motor	Same as motor
18. Size of mounting side (Width x Height)	-	-	-
19. Output signals compatible with control system	Yes	Yes	Yes
20. Pulses per revolution	40 PPR	40 PPR	40 PPR

B

Appendix B: Redundant concept generation

In this appendix the concept generation for a mounting solution on a protruding round shaft was done. This was done since it was assumed a protruding round shaft was the connection that was available on the motor, however this assumption was incorrect. This concept generation was done before the real connection to the motor was discovered. When the correct connection was discovered these concepts were discarded since they had no further use for the project as a whole.

B.1 Concept generation - Mounting solution on round shaft

After the initial concept generation, deciding what type of sensors to investigate further, as well as what type of mounting solution was to be used, a second round of concept generation was started, focusing on the mounting solution using a friction mount. It was also stated that there was a preference for solutions that could handle multiple shaft diameters. With this in mind a second concept generation was started. A similar process to the first concept generation was performed, starting with individual brainstorming and external search, followed by discussing the ideas and coming up with even more concepts by doing the process once again in group this time. This ended up with 12 concepts that could potentially work which are presented in Table B.1. When discussed further some of the concepts were considered bad, a few were unnecessarily complicated or difficult to produce and a couple were deemed possible but not as good and so the concepts were narrowed down to 5 to be taken into further development and prototyping.

Table B.1: Concept drafts for the friction mounting

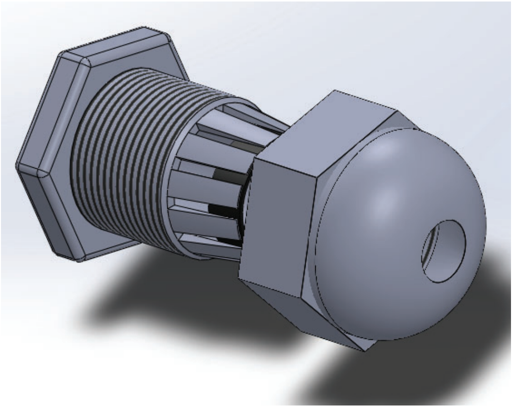
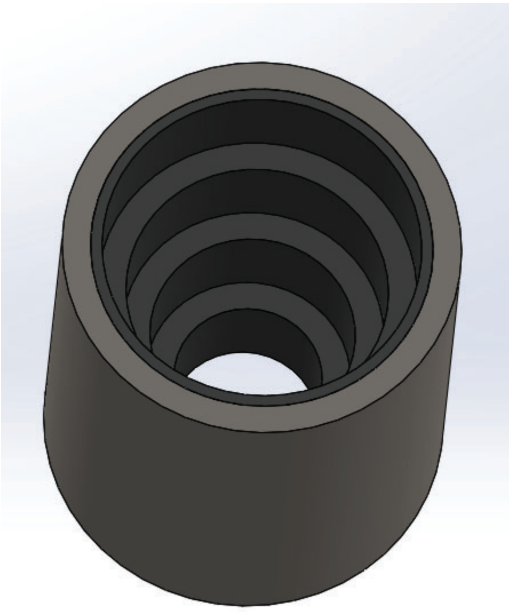
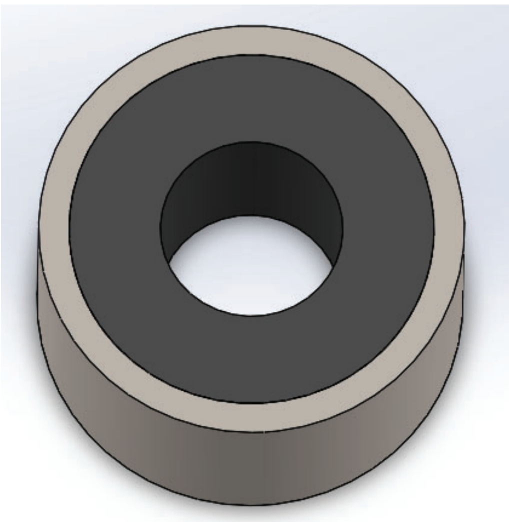
Concept no.	Concept draft	Description
1		Cable gland - interchangeable friction material depending on the motor shaft diameter, screws on to clamp down around the shaft.
2		Levels - Discrete levels of friction material for each motor shaft diameter.
3		Rubber distance - A simple rubber distance keeping the motor shaft in place. Different size of the distance depending on the motor shaft diameter.

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Table B.1: Concept drafts for the friction mounting (Continued)

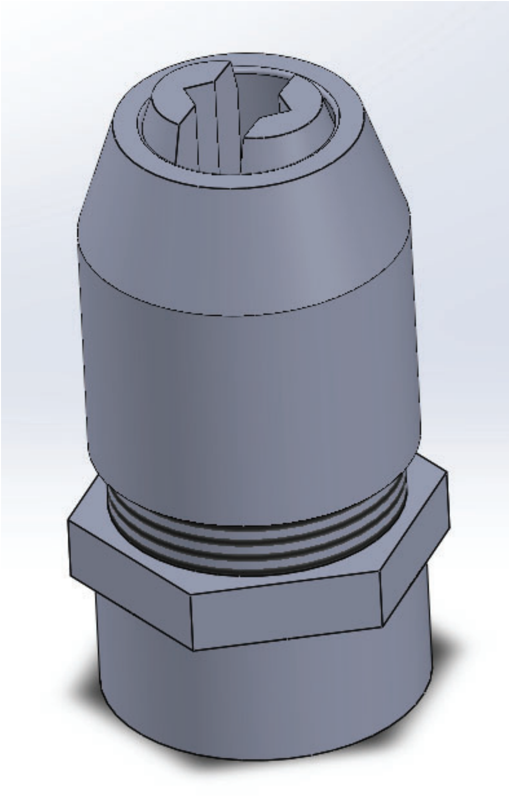
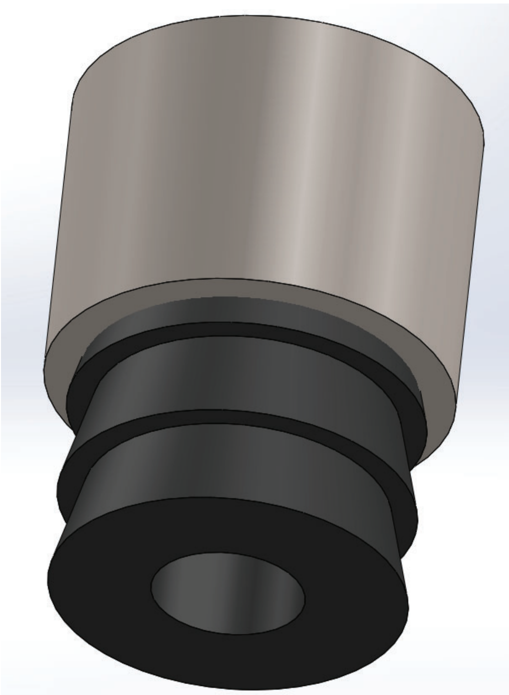
4		Drill chuck - The same mechanism as a drill chuck, screwing on and tightening an array of different motor shaft diameters.
5		Rubber multi cone - A conically ribbed rubber sleeve for the shaft that fits into the mount, keeping it in place. Change the sleeve depending on the motor shaft diameter.

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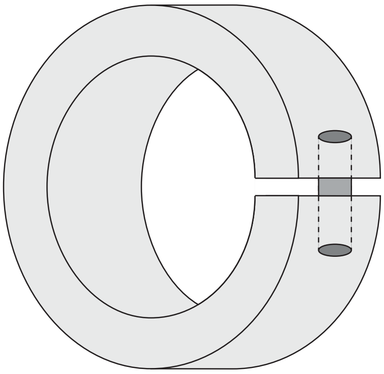
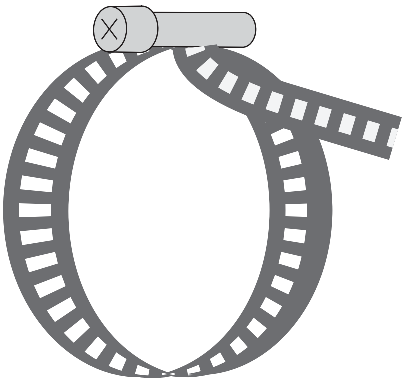
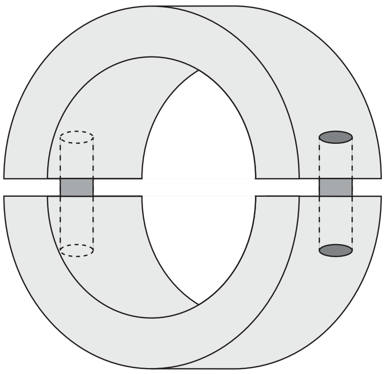
Table B.1: Concept drafts for the friction mounting (Continued)

6		Shaft collar - A readily available solution to clamp down on the motor shaft, may have difficulties properly clamping and centering a wide array of motor shaft diameters.
7		Hose clamp - A readily available solution to clamp the motor shaft. May have troubles clamping and centering a wide array of motor shaft diameters.
8		Linear clamp/two piece shaft collar - Available solution clamping around the shaft, may have trouble centering the motor shaft.

Continued on next page

Table B.1: Concept drafts for the friction mounting (Continued)

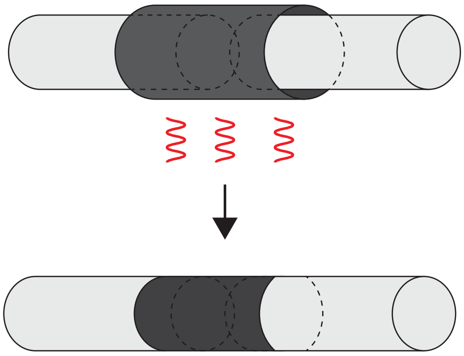
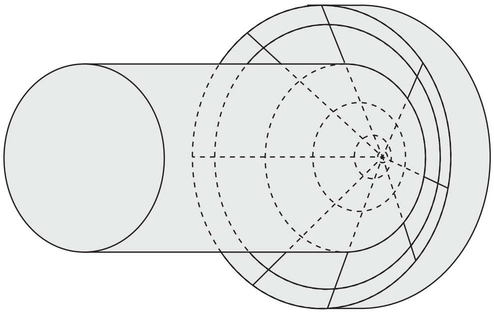
9		Guitar cable - Similar to a cable gland but based on the fact that the guitar cable is made from a flexible/elastic material.
10		Shrink tube - A rubber-like tube that shrinks when heated, used for connecting cables. Could connect two shafts, unclear how durable and strong it is to use for connecting rigid shafts compared to cables.
11		Cone - A simple conical fit for the shaft. May have too little connection surface and loosen with vibrations.

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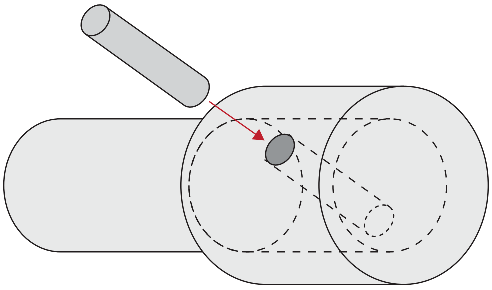
Table B.1: Concept drafts for the friction mounting (Continued)

12		Locking pin - A pin put through the shaft and a socket keeping them together. Requires modification of the motor shaft.

B.2 Concept selection - Mounting solution on round shaft

The five concepts that were kept for further development were modelled in CAD to display the different concepts and see which ones could be feasible. To select which ones to further develop simple prototypes were to be 3D-printed or cut out in order to see how well they would fasten the encoder and how easy they would be to attach to a motor shaft. Before any prototyping or selection could be done it was realised that a key assumption had been incorrect and thus these concepts were discarded.

C

Appendix C: Shaft simulations

C.1 Strength and rigidity simulations of the shaft

To ensure that the encoder would hold up in different cases of operation, a simulation of the finished shaft was done with the estimated forces that would appear. In the encoder the forces that would appear during normal operation are very low, since the only force working against the running of the motor is the bearing that the shaft is attached to. The case where the biggest forces would occur is when running the motor manually by inserting a hex handle in the bottom of the encoder and turning to make the motor run. This is mainly done during testing and if some error would occur in the motor, but to make sure that this is possible with the shaft dimensions selected a couple of simulations were done. Information from ASSA showed that the estimated torque that the shaft would be exposed to was around 8-10Nm. The simulations were done in solidworks where the shaft was fastened to support parts on both ends to simulate normal operation. A torque of 10Nm was then applied to one of the support parts while the other one was fastened, to try out the "worst case" scenario, where the full torque is applied to the shaft. Aluminum was chosen as the material of the shaft to achieve the wanted characteristics. The stress results can be seen in Figures C.1 and C.2. The maximum stress appears where the manual crank is to be inserted, at a value of 224MPa. With different aluminum alloys having yield strengths ranging from 50MPa to 500MPa, this shows that a bit of consideration needs to be taken when choosing the material of the shaft. One of the more common alloys is Aluminum 6061, which is also considered to be a low cost option, has a yield strength of approximately 270MPa, which should work fine for this application. Figure C.3 also shows the displacement of the shaft when the torque is applied. The maximum displacement is 0.265mm and appears on the outside of the shaft center. This should also not be a problem since such a small displacement will not affect the readings of the encoder or cause any collisions with other parts inside of it.

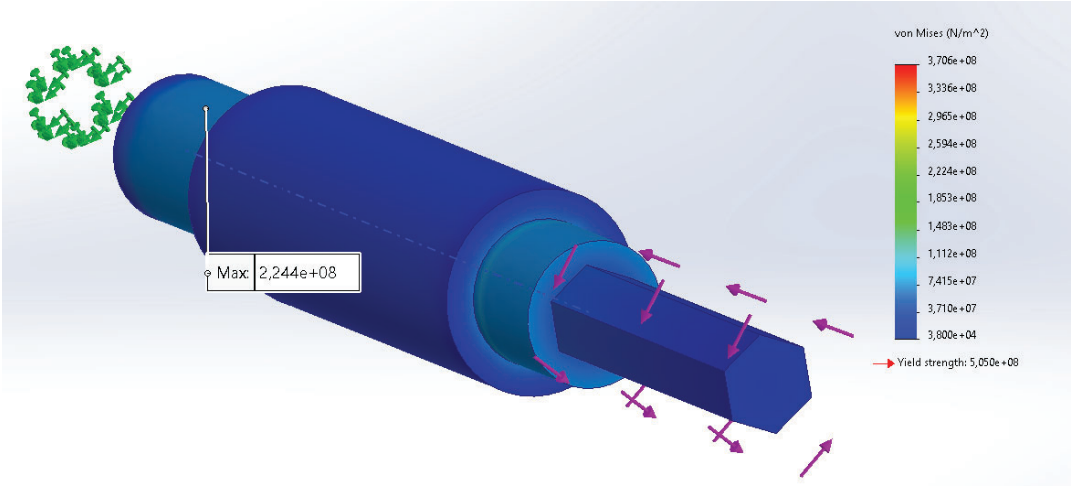


Figure C.1 Simulated stress results on the encoder shaft due to manual drive of the motor

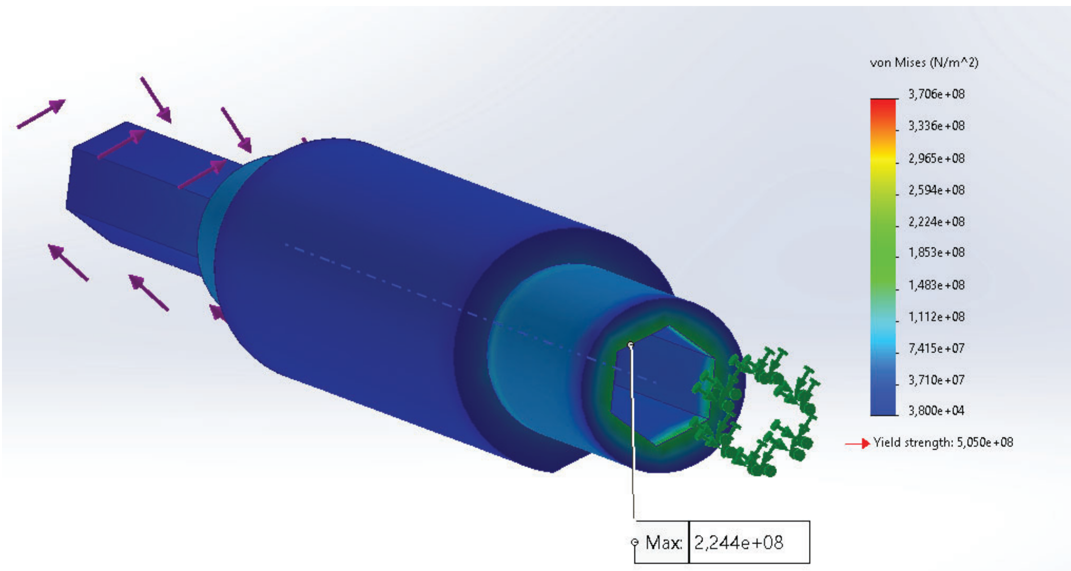


Figure C.2 Simulated stress results on the encoder shaft due to manual drive of the motor shown at a different angle

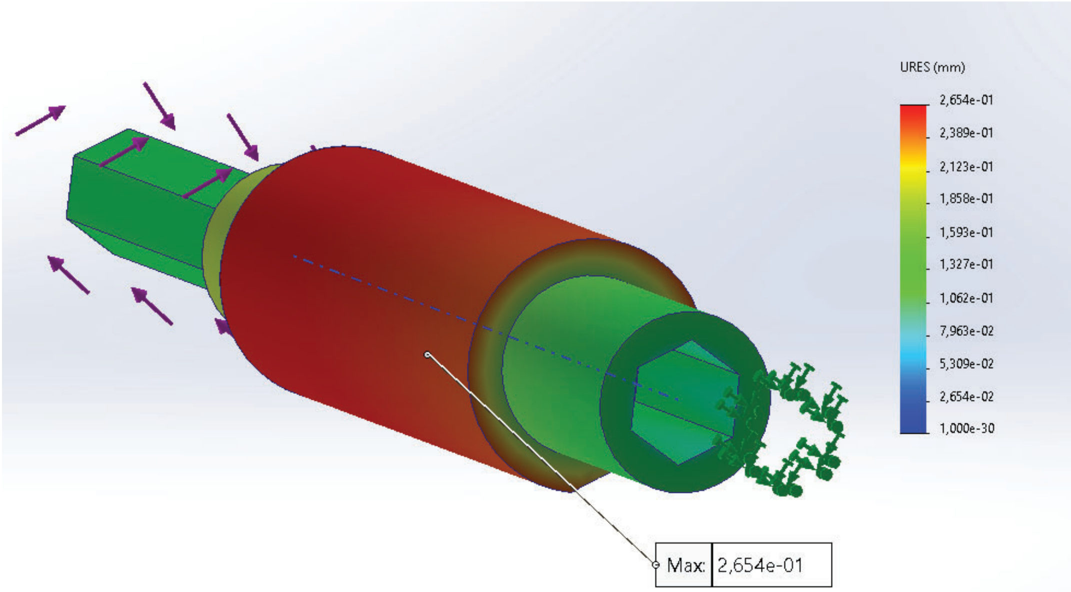


Figure C.3 Simulated displacement results on the encoder shaft due to manual drive of the motor