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E-Driver, an Electric Post Driver

E-Driver, en elektrisk stolpe driver

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E-Driver, an Electric Post Driver

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Preface

This master thesis is the final step of my 5 years of studies for the degree; Master of Technology at the Norwegian University of Life Sciences. The project work has been carried out at the Department of Mathematical Sciences and Technology, in close collaboration with the company Resonator A.S. The aspects of my degree that interests me the most is mechanical and electrical engineering, it was therefore important for me to choose a project within this field. When my advisor suggested to talk with the company Resonator A.S., and they explained what they wanted to develop, it seemed very interesting. My main motivation for writing the thesis in collaboration with Resonator was to be able to learn about electrical motors, and the possibility of being able to develop a new product with their technology. Vibrations and their applications in machinery and as a driving force is not a field that has been thoroughly explored, this makes it very interesting to learn more about this technology. The master-thesis is structured after a standard product development method.

I would like to thank Associate Professor Jan Kåre Bøe for help with structuring the master thesis, CEO Svein Hestevik for the idea and assistance, Ravindra Babu Ummaneni for help with electrical components, Master of Science André Dahl Jacobsen for help with the dynamic model, Anita Sauar Omvang for proofreading, Chief Engineer Tore Ensby for help with main design, Senior Engineer Bjørn Brenna lending workshop equipment and advice, Senior Engineer Gunnar Torp for help with machining, Technician Tore Brænd for workshop tips, workshop trainee Patrick Porsblad Kise for help with machining and my advisor, Associate Professor Odd Ivar Lekang, for getting me started.

Ås, 15 mai 2015

Anders Omvang

Abstract

This project is based around Resonator´s patented idea of a linear electric motor. This motor can be used for many different applications, and in this thesis three ideas has been considered. The idea that was selected through a screening process is to use the Resonator motor in a handheld electric post driver. This master thesis describes the research done regarding post drivers and the development, prototype production and testing of a novel handheld electric post driver. The post driver shall be driven by a battery, be lightweight, cheap and efficient for use with posts up to 100mm in diameter. During the market research it is confirmed that there is potential for a cheap lightweight electric post driver. Theory and technology necessary for developing the product has been researched, and the most problematic aspect found is to keep the weight of the driver within reasonable limits. The concept was tested with a simple drop test, to make sure the design impact power would be enough to drive the posts into soil. The development process was then done in two stages. The first stage was the functional design, where the different motors that Resonator had available were considered, and new solutions proposed. Most options were discarded as a result of too much weight. The chosen solution consists of modifying and rebuilding the simplest of the Resonator motors into a much more powerful motor, based on the same simple design. This keeps both the weight and the production costs to a minimum. However, since Resonator did not have the required permanent magnets at hand, a similar solution that will give approximately the same result as the chosen solution, but fits the available magnets, was prototyped. The prototype was first tested in a test stand, to make sure it was functioning correctly, then on a 80mm in diameter post, placed in a bucket of soil. The post was successfully driven into the soil with sufficient speed. The maximum penetration rate was found at 27.5 Hz, for the given soil conditions. This gave a corrected penetration rate of 83cm/min. Some issues were discovered during the testing, which were valuable in further developing the product. With the functional design complete, the process of further concept development started, where all the functions of the product that was mapped in the functional analysis were evaluated. Different design solutions is proposed for each function, and a screening process is implemented to select the best solutions. The final design solution is then drawn in a CAD program. This model is used to consider the environmental impact of different materials, calculate the complete weight of the new design, illustrate the product in a market presentation and make workshop drawings. An economic evaluation of the product and production costs has been done, and it is estimated that minimum 698 products must be produced in order to reach a shelf price of 10 000 NOK.

Sammendrag

Dette prosjektet er basert på Resonators patenterte idé av en elektrisk lineær motor. Denne motoren har mange forskjellige bruksområder og i denne masteroppgaven har tre forskjellige idéer blitt vurdert. Idéen som ble valgt gjennom en screening prosess er å bruke Resonator motoren i en håndholdt elektrisk stolpe driver. Denne masteroppgaven beskriver studiet gjort av stolpe drivere og utviklingen, prototype produksjonen og testingen av en ny elektrisk stolpe driver. Stolpe driveren skal drives av et batteri, være lett, billig og effektiv for bruk med stolper opp til 100mm i diameter. Fra markeds undersøkelsen kommer det frem at det er et potensial for en billig, lett elektrisk stolpe driver. Teori og teknologi nødvendig for utviklingen av produktet er undersøkt, og det mest problematiske aspektet funnet er å holde vekten til produktet innenfor rimelige grenser. Konseptet var testet med en enkel drop test, for å verifisere at design kraften er nok til å drive stolper i jorda. Utviklingsprosessen var så gjort i to trinn. Det første trinnet var det funksjonelle designet, hvor forskjellige motorer som Resonator hadde tilgjengelige ble vurdert, og nye alternativer foreslått. De fleste alternativene ble forkastet på grunn av for mye vekt. Den valgte løsningen består i å modifisere og ombygge den enkleste av Resonator motorene til en mye sterkere motor, basert på det samme enkle designet. Dette holder både vekten og produksjonskostnadene til et minimum. Men, siden Resonator ikke hadde de nødvendige permanent magnetene tilgjengelige, ble en liknende løsning som vil gi omtrent de samme resultatene som den valgte løsningen, men passer de tilgjengelige magnetene, prototypet. Prototypen ble først testet i en test rigg, for å være sikker på at den fungerte skikkelig, så på en stolpe med 80mm i diameter, plassert i en bøtte med jord. Stolpen ble vellykket drevet ned i jorda med tilstrekkelig hastighet. Maks penetreringshastighet ble funnet ved 27.5 Hz, for den brukte jordtypen. Dette gav en korrigert penetreringshastighet på 83cm/min. Det ble oppdaget noen problemer under testingen, disse var verdifulle i videreutviklingen av produktet. Med det funksjonelle designet bestemt startet prosessen med videreutviklingen av produktet, hvor alle funksjonene til produktet, som ble kartlagt i funksjonsanalysen ble vurdert. Forskjellige design valg ble foreslått for hver funksjon, og en screening prosess er brukt for å selektere de beste løsningene. Det endelige designet er så tegnet i et CAD program. Denne modellen blir brukt til å vurdere miljø påvirkningene av forskjellige materialer, regne ut den komplette vekten av det nye designet, illustrere produktet i markedspresentasjoner og lage verkstedstegninger. En økonomisk analyse av produktet og produksjonskostnadene har blitt gjort, og det er estimert at minimum 698 enheter må produseres for å oppnå en hyllepris på 10 000 NOK.

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1 Introduction

This master thesis is written for the company Resonator, who has patented what they call a "Resonator", patent number 325266, which is a method of transferring energy in a linear electrical machine, driven by gas springs. The concept is built around a piston made out of permanent magnets, traveling in a sealed tube surrounded by electrical coils, when a current is flowing an electric field is induced that works on the piston. By switching the direction of the current the direction of the force on the piston will also change, this causes the piston to move back and forth. Resonance is achieved in the machine when the piston and stator are moving in synchronization with the electrical current. . Resonance amplifies the power output and the efficiency of the system. This is the key principle behind the patented technology of the Resonator. Resonator´s primary business idea is developing tools for wireline oil well interventions and rent these tools to the operators. They are currently developing a hammer drill for drilling after oil, water etc. However they have plenty of other ideas of what the Resonator could be used for. This thesis will be exploring different applications of the Resonator. Three ideas will be considered, and the one that seems most promising will be developed, prototyped and tested. For the product development process Integrated Product Development (IPD), is used, this is a method that incorporates a lot of different aspects into the early process, to eliminate problems later. It requires the use of computer assisted design and planning.

1.1 Presentation of Ideas

The Swimming Animal
This idea is based on a linear vibrating machine that is formed like a torpedo with a special type of finns, can be made to swim in one direction underwater. If this is possible, the Resonator can be used to pull different objects underwater. An example of such use is pulling cables through a pipe underwater, since these cables have a tendency to get stuck on the pipe wall if they are pushed for a long distance. Resonator have already explored this idea with other research papers, and they have verified that it is possible to get a one directional movement with vibration. The goal would then be to develop this product, and design the finns so they give optimal movement.

The Electric Post Driver
This idea is about using the Resonator, driven by a battery, to drive posts into soil. The Resonator is installed in a tube, which is mounted on the post. The post is then driven by the linear vertical vibrations or strikes. The goal is to make a product that is light, cheap and easy to use. There is no previous research with using the Resonator for driving posts, this idea therefore requires that some research and testing is done before a concept can be decided.

The Damping Generator
This idea is about using the Resonator as a generator instead of a motor. If the resonator can be modified to act as a damping spring in addition to a generator it can be used to create electricity from vibrations and at the same time act as a damper. This can for example be used instead of regular dampers in a car, to improve the regeneration of electricity in electric and hybrid cars. It can also potentially be used in industry with big vibrating machines. These are usually resting on big dampers to avoid transferring these vibrations to the rest of the area around. These dampers can be replaced with modified Resonator`s to regenerate power. There is no previous research within Resonator on this subject.

1.2 Idea Selection

In the selection of the most promising idea, Stuart Pugh`s method is used. This is a method to control the validity and quickly narrow down the most promising ideas. The ideas are graded on different criterias, with (-1), (0) or (+1). These scores are summed up to see which ideas score the most points. The criterias are based on attributes that makes it likely for the idea to succeed.

The criterias that the ideas will be graded on are:

- Originality – An idea or improvement that is novel.
- Complexity – To which degree a component consists of many different parts, that requires knowledge in different technical fields to understand.
- Usefulness – If the product can be used for something productive.
- Timeframe – If it is possible to develop the product satisfactorily in the given timeframe.
- Cost – Estimated cost of developing the product, building a prototype and testing it.
- Potential – Is it possible to sell a big or small amount of the product?

Table 1.1: Selection table, based on Stuart Pugh´s method.

Criteria	Swimming animal	Electric Post Driver	Dampening Generator
Originality	+1	0	+1
Complexity	-1	+1	0
Usefulness	0	+1	+1
Timeframe	0	+1	0
Cost	-1	+1	0
Potential	+1	+1	+1
Sum	**0**	**+5**	**+3**

1.3 Chosen Concept

The concept that was chosen to be developed is the **Electric Post Driver**.

From Table 1.1 the electric post driver clearly comes out on top. This is mostly because it consists of fewer technical aspects, which makes the design process less complicated and it is estimated to cost less to prototype and test compared to the other ideas. This gives a higher probability of developing a finished and working product. However it scores less than the other ideas on originality, since it is not a completely new product, but it can still be a significant improvement to current solutions. Recent years has seen a steep decline in hard manual labor, especially in the western world. Development of new and better machines keep making our lives more comfortable, and the post driver can be yet another such machine.

1.4 Competitors on the Market

1.4.1 Manual post drivers

This is a post driver without any power source, it must manually be lifted into the air, then slammed down onto the pole repeatedly to drive the pole into the ground. This is easier than using a sledgehammer, as you don't have to aim, but it is still exhausting work, and not easily done for everyone. These post drivers typically weigh around 6-20 kg and needs to be slammed around 10-30 times onto the pole to drive it sufficiently into the ground. They cost around 1000 NOK. The lighter the post driver is, the more downward force is required of the operator.

Figure 1.1: Manual post driver being used to drive a wooden post. Source: http://www.gustavsenas.no/

Table 1.2: Table showing average data of manual post drivers.

Price range	Approximate 1000 NOK
Power	Approximate 45 J or above
Impact frequency	Manual
Weight	8-20 kg

1.4.2 Gasoline driven post drivers

These post drivers are driven by small motors, which are attached to the post driver. The motor drives a piston with a hammer mounted at the end, which repeatedly strikes the top of the post. The motors have a very high impact frequency, which causes vibrations that can be uncomfortable for the operator. To counteract this issue the gasoline driven post drivers are usually equipped with vibration dampers. They also have both vertical and horizontal handles. They are quite light, but require refueling and lubricating in order to function.

Figure 1.2: Petrol engine from honda mounted on a post driver. Source: http://www.petrolpostdriver.com/

Table 1.3: Average data collected from gasoline post drivers

Price range	15 000-20 000 NOK
Power	26 J
Impact frequency	1 500 – 2 000 BPM
Weight	15-20 kg

1.4.3 Hydraulic post drivers

Hydraulic post drivers work on the principles of pressurized systems. These are the most powerful of the handheld post drivers. Since fluids cannot be compressed hydraulic systems can transmit high forces rapidly and accurately. The piston is driven by pressurizing liquid into a chamber on one side of the piston, which then puts pressure on the chamber walls, if one of these walls are one side of the piston, the pressure will push it away. A valve is then turned that releases the pressure in this chamber, and pressurizes a chamber on the other side of the piston, this causes the piston to move back and forth. In high-pressurized systems it is normal to use mineral oil, as this will also lubricate and protect the internal parts of the machine and it can sustain high temperatures.

Figure 1.3: Hydraulic post driver. Source: https://www.crowderhydraulictools.com/

Table 1.4: Average data collected from hydraulic post drivers:

Price range	15.000 – 30.000 NOK
Power	24 – 110 J
Impact frequency	1320 – 2300 BPM
Weight	17-40 kg

1.4.4 Pneumatic post drivers

Pneumatic post drivers are built on the same principles as the hydraulic, except these are not able to deliver the same high forces, since gas can be compressed. There are different pneumatic post drivers on the market today some uses the pressurized air to push the post driver up, but the operator must manually slam it back down onto the post. By not having to lift the post driver the operation becomes much easier for the operator, especially if working for a long duration. This post driver is very cheap compared to other ones, but also much less effective. Other pneumatic post drivers work like a hydraulic post driver, where a piston inside the driver is hitting the post.

Figure 1.4: Pneumatic post driver. Source: http://www.northerntool.com/

Table 1.5: Average specifications of pneumatic post drivers.

Price range	3.000 - 30.000 NOK
Power	manual – 0.6 MPa and 1200 l/m
Impact frequency	manual – 1700
Weight	16-25 kg

1.4.5 Gas driven post drivers

The gas driven post drivers look and work much the same as the gasoline driven post drivers. With a gas driven engine attached to the post driver. These post drivers are also usually fitted with vibration dampers in the handles. It is promoted as the “perfect tool for agriculture, livestock containment, electrical utility and more” (Rhino Tool company , 2015).

Table 1.6: Average data collected from gas driven post drivers:

Price range	15 000 – 25 000
Power	1.3 hp
Impact frequency	1500 – 2000 BPM
Weight	15-20 kg

Figure 1.5: Gas driven post driver. Source: http://www.russopower.com/

1.5 Market Needs and Potential

Post drivers are used to mount a lot of different types of poles into the earth. This can easily be done by large and expensive machines, however for the normal user this is not an option. In Norway especially we have a lot of small farmsteads, and the posts are usually driven by manual tools, either sledgehammers or a manual post driver, which has to be lifted and slammed upon the posts. Several different types of handheld post drivers exist, but they are usually very expensive and require a lot of accessories. For example the hydraulic driven post driver, where you need input of pressurized liquid, this makes it difficult to move around. A more mobile solution are handheld post drivers driven by a gas or gasoline engine, however they are very expensive.

In the Norwegian post driving market motorized post drivers are very unusual. You can buy manual post drivers in stores, but if you want a pneumatic, hydraulic or motorized post driver you have to order it from another country, the United States for example has a much larger market. If it is possible to develop a safe electric post driver affordable for most people, the potential for the product is promising.

In order to be able to compete with the existing market solutions, the electric post driver must as a minimum be within the following limits:

Table 1.7: Specification demands to compete in the current market.

Price	Below 10 000,- NOK
Power	Minimum 20 J
Impact frequency	Irrelevant
Weight	Below 20 kg

1.6 Patent Research

Patents in both Norway and the US were checked, one other electric post driver patent was found in the US. However it is a radically different design and will not conflict with developing an electric post driver driven by a linear electric motor. In the US some patents were also found with regards to a damping mechanism for post drivers and for ornamental design. These patents must be considered if the product is to be sold in the US. In Norway no conflicting patents were found. Additional patent research must also be done for each country if the post driver is to be sold in an international market.

The design of manual post drivers has not changed much since patented by Ernest, Hunt in 1937, see Figure 1.6.

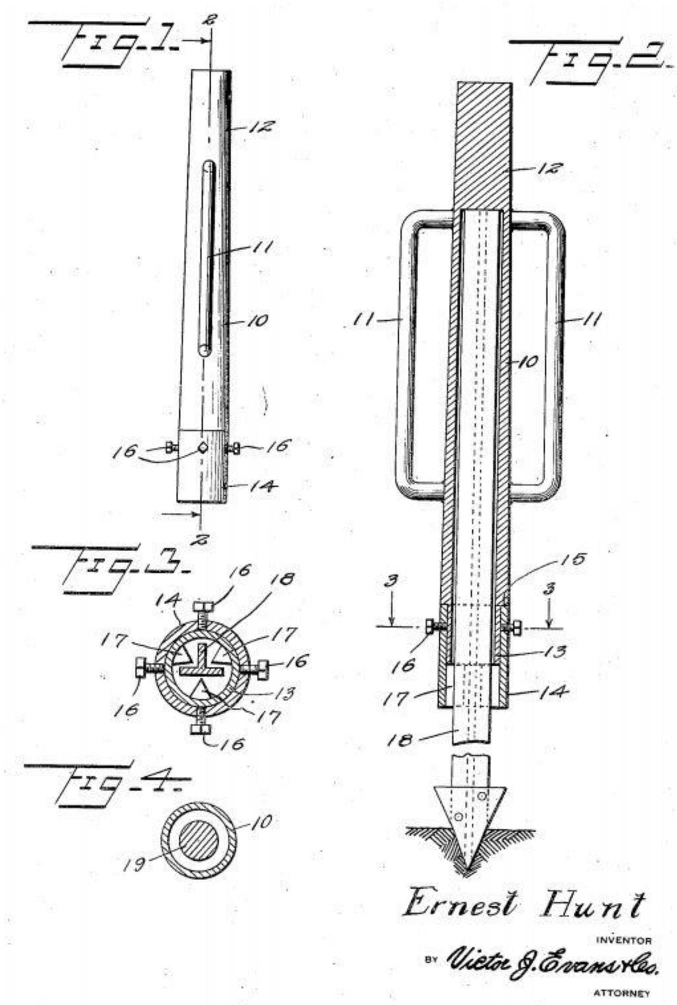


Figure 1.6: Illustration of patent by Ernest Hunt from 1937. Source: http://www.freepatentsonline.com/

2 Project Plan

Project goals and a project plan is set up after Gantt principles. It is important to organize the work systematically to avoid confusion along the way, as well as clear goals and part goals of what the process is meant to achieve in the end and along the way. The part goals are especially important in the development process, as each part goal is a milestone in the work plan. The part goals are like steps to the final goal. That means when all the part goals have been completed, the final goal shall also be complete. The work plan further details the process in a schedule, with the part goals as a milestone to be reached at the end of each important task.

2.1 Project Goal

The following project goal has been defined for the work which shall be reported:

Developing a novel and cheap post driver that can be operated by hand, is powered by a battery source and driven by a linear electrical motor. Furthermore present the stages of the development process, findings and results in a final Master-report.

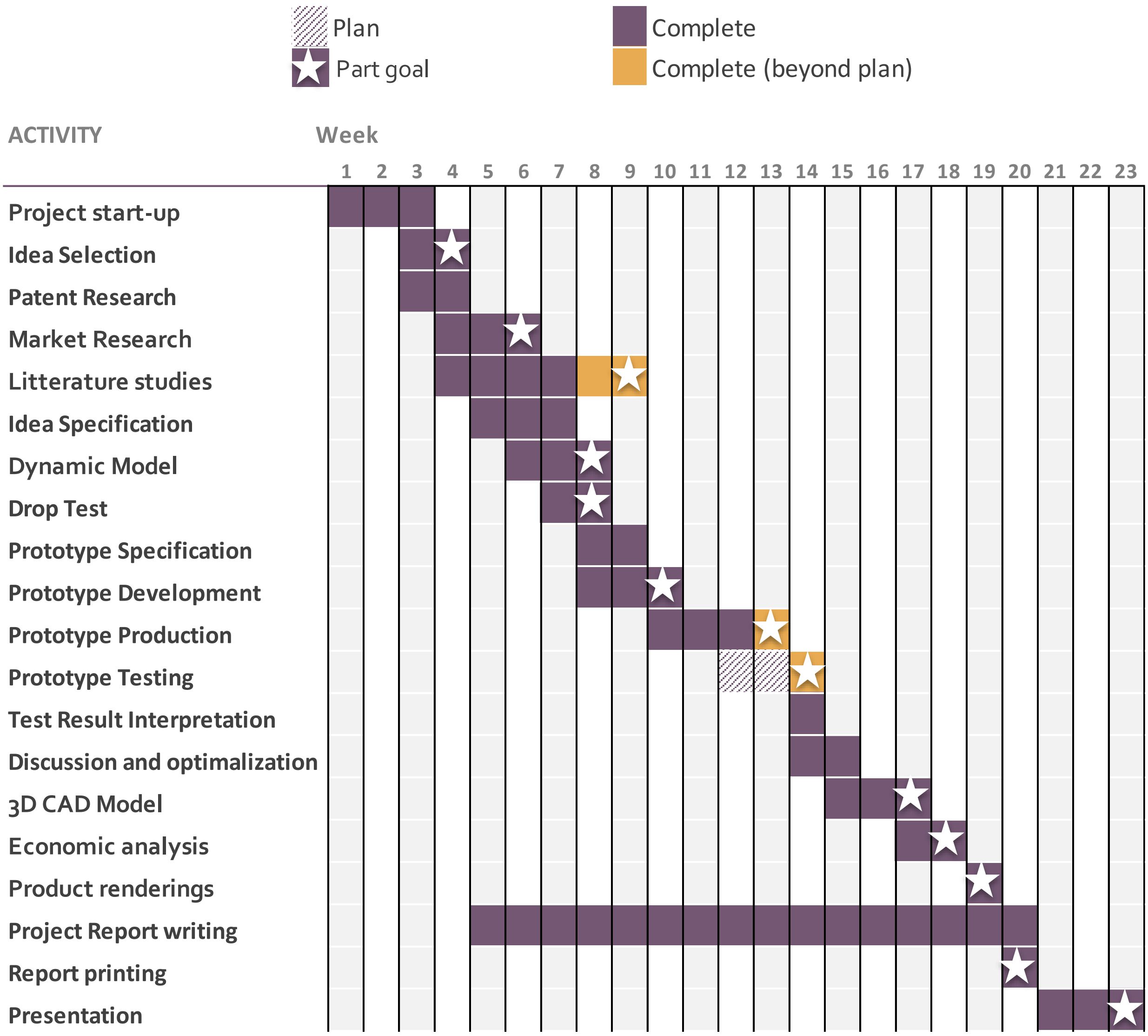
2.2 Part Goals

- Define and select a concept to develop.
- Analyse market needs and potential for the product.
- Research litterature and patents in regards to post drivers to build a preliminary base of theoretical knowledge.
- Develop a model for the dynamic movement of the post driver.
- Verify the required impact energy to drive a regular post into soil with drop tests.
- Design a prototype post driver after chosen specifications.
- Fabricate and assemble the prototype.
- Test the prototype, with different parameters.
- Develop the 3D CAD model from the chosen design solutions.
- Analyse the economic aspect of producing the product.
- Create renderings of the product for market presentation.
- Finish the Master-report and presentation.

2.3 Work Plan and Milestones

this is a type of bar chart first developed by Henry Gantt in 1910, that illustrates a project schedule. in order to have a systematic process, not get lost in some work and to complete the necessary parts in the timeframe given.

Table 2.1: Project plan after Gantt principles.



2.4 Limitations

Due to time limitations the following will not be included in the project work:

- The dynamic model for the system is modelled as a two spring system, with the top spring securely fastened. This is a simplification and optimization of the real model, as the top spring will realistically also get vertical movement. The consequences of this is that the real resonance frequency will be different from the output in the model. This will be solved by varying the frequency during testing, and finding the most efficient frequency, which will then be the resonance frequency.
- The electrical control unit for the machine is not included in the design.
- No electrical cables, except for the windings are included in the CAD.
- A method of fastening the post driver to the post is not included in the CAD.
- Packing and shipping of the product is not considered.

3 Methodology

The methodology is the theoretical basis for which methods are used and it defines the technical terms needed to understand the research and study.

3.1 Terminology

This chapter lists all definitions, symbols and units used in the master-report.

3.1.1 Definitions

Table 3.1: Terms and descriptions

Term	Description
E-Driver	The novel electric post driver developed in this master-project
RMS current	Root mean square value of the current values
BPM	Beats per minute
NOK	Norwegian Krone
CAD	Computer Assisted Design

3.1.2 Symbols and units

Table 3.2: The international system (SI) of units, with symbols and abbreviated units.

Name	**Symbol**	**SI Unit**	**Unit abbreviation**
Length	l, x	meter	m
Mass	m	kilogram	kg
Density	p	kilogram/volume	kg/m^3
Volume	V	liter	L
Speed	v	meter/second	m/s
Pressure	p_p	Pascal	Pa
Time	t	second	s
Damping coefficient	c	newton-seconds per meter	Ns/m
Spring stiffness	k	newtons per meter	N/m
Pi	π	-	-
Angular frequency	w	radians per second	s^{-1}
Current	i, I	ampére	A
Frequency	f	hertz	Hz
Force	F	newton	N
Potential energy	E_p	joule	J
Kinetic energy	E_k	joule	J
Power	P	watt	W
Voltage	V	volt	V
Electric field intensity	E	volt/meter	V/m
Electric flux	ϕ_E	volt meters	V m
Electric flux density	D	coulomb/square meter	C/m^2
Magnetic flux	ϕ_m	weber	Wb
Magnetic field intensity	H	ampére/meter	A/m
Magnetic flux density	B	tesla	T

Inductance	L	henry	H
Resistance	R	ohm	Ω
Conductance	G	siemens	S

3.2 Method and Development Tools

Integrated Product Development (IPD)

IPD is a product development method that is based on integrating different aspects of the development process, by frequent use of computer technology and procedures for planning and organizing. The goal is to achieve higher efficiency and a steeper learning curve from product development projects. An example of integrating different aspects is to consider both economic and environmental aspects of different solutions during the process, instead of discovering issues at the end, which can lead to necessary re-design(Bøe, 2014).

Function Analysis

Function analysis is used to reach an optimal design solution and get an overview of the different requirements to the product. The product is divided into its fundamental functions, which is then ordered in main and sub functions. This makes it easier to see new solutions by combining different functions in new ways. All of these different functions are then analysed and several solutions for each function is proposed. These solutions will then be considered in a concept screening, where each function is given specific criteria's and is rated thereafter (Bøe, 2014).

Pugh's Method

Pugh's method is a tool for choosing and sorting concepts and generating additional ideas. The method is based on setting up different criteria's that can be weighted, dependant on how important they are considered to the product. The different concepts are then graded with a score, ranging from 1-3 or something similar. This score is then weighted and the total weighted score indicates which concept is most likely the best solution (Bøe, 2014).

Patent search

Patent searches can be done online for different countries. This is best to do as early as possible, to ensure that no patents are standing in the way of the proposed design solution. If a conflicting patent is found it is important to first verify that it is up to date and valid. In such an event it might be possible to buy rights or co-operation from the patent holder.

If no patent already exists for the solution it is possible to apply for a new patent. The requirements for a new patent are: It shall be a practical solution to a problem, of technical character and that it must not have been published prior to the application. It must be a novel solution to the problem and the patent must be written so the solution is industrially reproducible (Justis- e Politidepartementet, 1968)

Computer Assisted Design (CAD)

Computer assisted design is used to illustrate and improve the product design. When the product is drawn in a CAD program, input can be given to components so that the model can be used to calculate weight, forces and stresses. This model is also used to produce workshop drawings.

Computer Software

- Solidworks 2014, Dassault Systèmes.
- CES Edupack 2014, Eco Audit function.
- Matlab 2014, The MathWorks, Inc.
- Simulink 2014, The MathWorks, Inc.
- Microsoft Word 2013, Microsoft Corp.
- Microsoft Excel 2013, Microsoft Corp.
- Paint 6.3, Microsoft Corp.

3.3 Process Chart

The development process is illustrated in Figure 3.1. Here we can see that there are a lot of stages that can lead to re-design, this is why the CAD design is placed so late in the process, to avoid having to re-draw and design new elements, as this is very time consuming. In the beginning of the design process research and innovation is the dominating factors. When the problem and solution has been clarified planning and organizing becomes an important factor. Specialists and external help that is necessary must be collected or made sure is available when it is needed. The most time consuming phase is the testing and development of the product. Here all the small details must be solved. The last phase is the CAD design, market presentation and economic evaluation of the product.

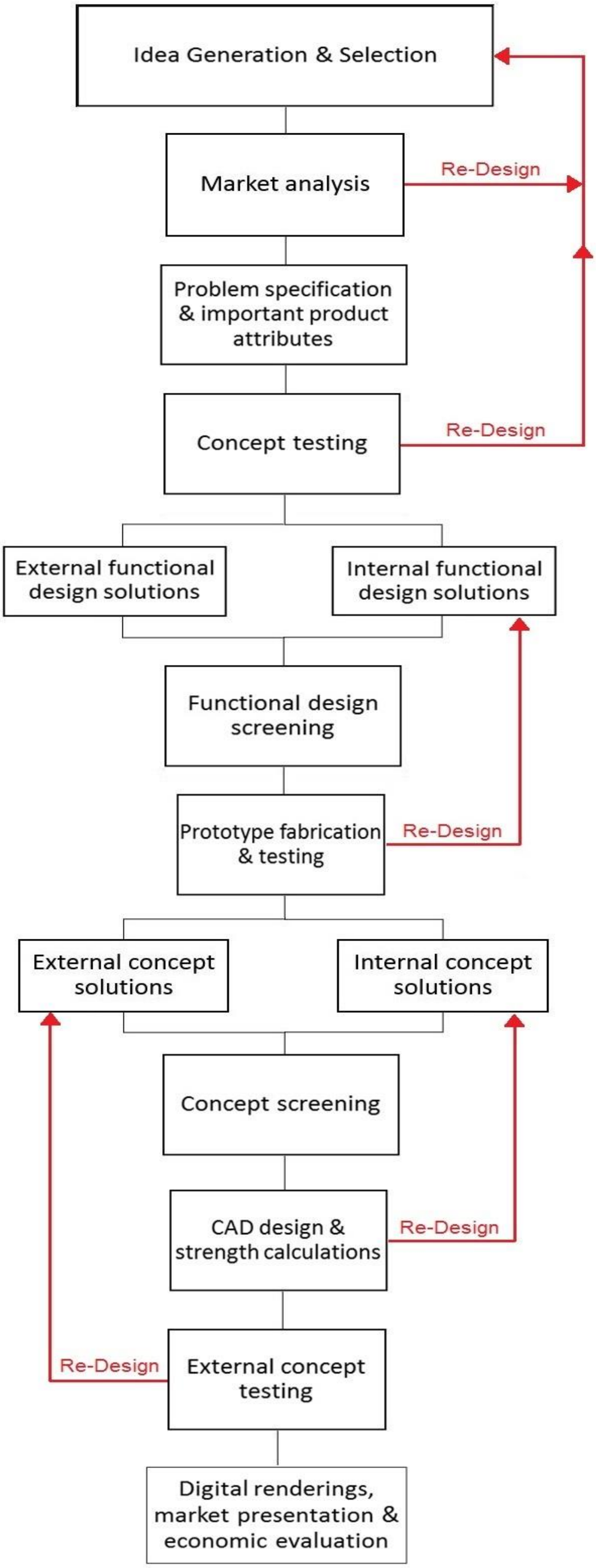


Figure 3.1: illustration of the product development process.

4 Theory and Technology

The E-Driver is a product type that has never been developed before, thus there can be unsolved technological challenges that must be addressed. This chapter will touch on the most important technological aspects that are relevant to an electric post driver.

4.1 Impact Theory

On the market today there are several different types of handheld post drivers. You can buy manual, hydraulic, pneumatic, gasoline or diesel or gas driven pole drivers. Larger machines connected to tractors or similar are also used as post drivers, but these are initially designed to be pile drivers, which drive much larger and taller poles into the ground for structural support. All the post drivers on the market today are governed by the fundamental principle of striking the top of the post repeatedly. The strike frequency, weight, power and efficiency of the different machines vary greatly.

The approximate impact energy necessary to drive a post into the soil can easily be calculated and tested using a manual post driver. The approximate impact energy can be calculated from the potential energy equation:

$$E_p = mgh \tag{4.1}$$

Where E_p is the potential energy, m is the mass of the object, g is the acceleration of gravity and h is the height the object is dropped from. Using a test weight of 10kg and a height 0.3m the impact energy will then approximately be:

$$E_p = mgh = 10 * 9{,}81 * 0{,}30 = 44{,}3\,J \tag{4.2}$$

Some energy will continue as kinetic energy in the other direction, as the post is slightly elastic.

The speed of the pole driver at impact can be estimated using the acceleration of gravity on the object, to attain the minimum downward thrust, the push from the operator is disregarded, and an estimated lift height of 0,3m is used.

$$v = \sqrt{2 * g * h} = \sqrt{2 * 9.81 * 0.3} = 2{,}43\,m/s \tag{4.3}$$

Where v is the speed of the object at impact. The average values of a manual post driver will be higher than these, since the operator most likely pushes down with force on each hit to drive the pole faster into the ground. However by doing drop tests it can be verified approximately what impact energy is necessary to continuously drive a post in a specific soil type.

4.2 Soil Theory

The definition of soil is an extremely wide term. Every kind of soil can be called by the same name, and yet the attributes can be complete opposites. We can differ from soil and topsoil, where topsoil is the top layer with high amounts of organic material. The composition of soil also varies, with how much clay, rocks, organic material, sand, water etc it contains. These factors will affect the penetration resistance of the soil. What kind of soil one thinks about is very dependant on someone´s background, for example a chemist, an engineer, an electrician and a biologist will probably all define “soil” differently. This can cause a lot of confusion when using this term. The engineering definition of soil, which is the definition used in this thesis, can be stated as “material that can be worked without drilling or blasting” (Whitlow, 1995). The composition of soil can be classified as in Table 4.1.

Table 4.1: Soil classification system (ASTM International, West Conshohocken, 2011).

Letter	Definition	Letter	Definition
G	Gravel	P	Poorly graded (uniform particle sizes)
S	Sand	W	Well-graded (diversified particle sizes)
M	Silt	H	High plasticity
C	Clay	L	Low plasticity
O	Organic		

From Table 4.1 a soil type MW would then be a well-graded silted soil; this is a fine graded soil with particles in a wide range of sizes within the “silt” category. Silt usually has particle sizes between 0.002 and 0.06 mm.

Soil is split into three parts, soil, water and air. The different mixture of these components greatly affects the properties of the soil and the resistance to penetration.

There are several methods for measuring the soil penetration resistance of a field. The two methods most commonly used are The standard penetration test (SPT) and the cone penetration test (CPT). For the purposes of post driving the Cone Penetrometer test is most applicable. the CPT test can further be divided into a static and dynamic penetration test. In the static test, a cone of 3.58 cm diameter and 60 degree angle is pushed quasi-statically through the underlying ground at a speed of 10-20 mm/s. In the dynamic testing method a hammer that strikes with a constant force is used, and the number of hits until a desired penetration length is recorded. The force necessary to move the pile can then be calculated from the power of the strikes on the pile (Vipulanandan, Puppala e Jao, 2008).

Because of all the variables in determining the resistance to penetration it is not possible to calculate one specific value to design for. Instead the pole driver should be designed for worst possible condition, with adjustable frequency to tune it to the specific soil. The resistance to penetration also varies with the penetration depth, to be able to vary the frequency can be effective for not getting the pole stuck.

4.3 Vibratory Pile Driving Theory

A pile driver is a machine that drives piles into the ground, used to provide support for structures. Since this is a wide spread technology used all over the world, a lot of research has been done on this subject. Vibratory pile driving started in 1930 in Germany and the first commercial application was carried out by Hertwig already in 1932. There are two types of vibratory pile driving, “slow” and “fast” vibrodriving. German and French engineers, designed high frequency machines for use in Western Europe, with frequencies above 50 Hz, however they quickly discovered that the “fast” pile drivers didn´t have a long operation time. This was caused by high rates of wear in motors and bearings. This has caused the development with “fast” vibrodrivers to stop, and frequencies below 25 Hz to most commonly be used (Rodger e Littlejohn, 1980). With this type of pile driving it is necessary to clamp the machine to the post, then it is possible to transfer forces in both vertical directions, this transfers the vibrations to the pile.

4.4 Spring Theory

A spring is an elastic device used to store energy. The most normal type of spring is a coil spring (helical spring). It is a mechanical device made from a coil or wire. When the coil spring is pulled/pushed, it stores up energy, and then releases it by returning to its original state. In the E-Driver 3 springs are used and two of them are precompressed.

Basic Laws and Equations

Newton´s second law of motion which explains that the vector sum of all external forces on an object is equal to the rate of change of its linear momentum in an inertial reference frame (Tipler & Mosca, 2007).

$$\sum F = \frac{dp}{dt} = \frac{d(mv)}{dt} = m\frac{d^2x}{dt^2} = ma \tag{4.4}$$

Where $\sum F$ is the sum of all external forces, dp is the change in linear momentum, dt is the time and a is the acceleration of the object.

Hooke´s law of proportionality between force and extension is defined as (Tipler & Mosca, 2007):

$$F_k = -kx \tag{4.5}$$

Where F_k is the spring force, k is the spring stiffness and x is the distance the spring is displaced from its equilibrium position.

Total forces acting on a mass in a linear system with a mass, a spring, damping and a driving force (Tipler & Mosca, 2007):

$$\sum F = -kx - cv + F_0 \sin wt \tag{4.6}$$

Where c is the damping coefficient, F_0 is the driving force, w is the angular frequency of the force and t is the time.

Implementing **Newton´s second law** on the system gives:

$$m * \frac{d^2x}{dt^2} = -kx - c\frac{dx}{dt} + F_0 \sin wt \tag{4.7}$$

This can more easily be written as **the differential equation of motion** of a single-degree-of-freedom system, where the dot over the x represents derivation.

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin wt \tag{4.8}$$

The four terms represents the inertia force, the dampening force, the spring force and the external force.

The Natural frequency of two springs is defined as (Palm, 2006):

$$w_n = \sqrt{\frac{k_1 + k_2}{m}} \tag{4.9}$$

With two pre-compressed springs, the forces acting on the springs by Newton´s second law will be:

$$\sum F = ma = k(x_0 - x) - k(x + x_0) = kx_0 - kx - kx - kx_0 = -2kx \qquad (4.10)$$

Where x_0 is the initial state pre-compressed and x is the displaced state. This entails that the spring stiffness of the system will be the double of the spring stiffness of one spring, when the springs are pre-compressed.

Degrees of freedom

The number of degrees of freedom that a system possesses is the same as the number of coordinates that are necessary to completely define its configuration. The maximum number of degrees of freedom an object can have is six. Where three is rotational and three is directional. The total number of degrees of freedom for a system to have is found by multiplying the number of masses with the number of possible types of motion for each mass. The dynamic system in question has two degrees of freedom, this is because it has two masses, and one direction of movement. The system then also has two natural frequencies, in which it will vibrate naturally (Palm, 2006).

The two natural modes

The first mode is to be avoided in the post driver system, as in this mode the piston and stator are moving in the same direction, and no force will be created by the current working on the magnets. For the machine to work the piston mass and stator mass must have a relative speed to each other. This is what happens in mode two, where the two masses are swinging opposite to each other. This is the frequency that the machine must be designed for.

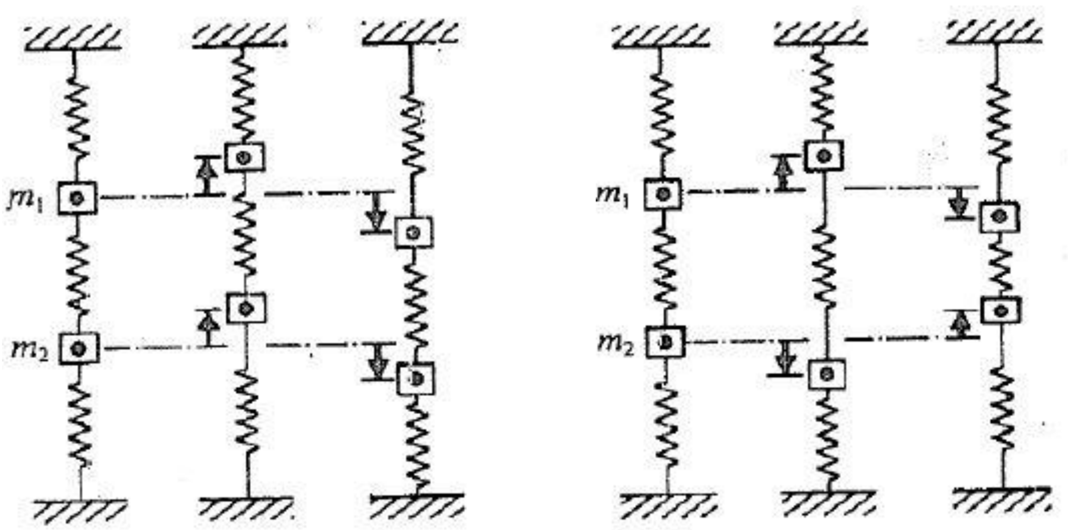


Figure 4.1: Natural swinging modes for a two mass system, the system on the left is the first mode, and the system on the left is the second mode. Source: http://web.itu.edu.tr

Forced vibrations

This is a system sustained by an external source of energy, this system will continue to vibrate as long as the supplied force is higher than the dampening force (Palm, 2006).

For a system consisting of one external force, one damper and one spring forced out of its equilibrium position, the **resultant forces** will be as following:

$$\sum F = -kx - c\frac{dx}{dt} + F_0 \cos(2\pi f * t) \qquad (4.11)$$

Where f is the frequency, representing the number of cycles per unit time.

Using **Newton´s second law**:

$$m\frac{d^2x}{d^2t} = -kx - c\frac{dx}{dt} + F_0\cos(2\pi f * t) \tag{4.12}$$

The steady-state solution to this equation is from practical experience known to be a simple harmonic motion, with frequency equal to the forcing frequency.

The post driver machine has two springs (the internal springs are mathematically considered as one spring with double stiffness due to precompression), two dampers and two masses as shown on the figure. When this system is forced out of its equilibrium position it will give the following **resultant forces** by using **Newton´s second law**:

$$\begin{aligned}\sum F_2 &= m_2a_2 + c_2(v_2 - v_1) + k_1(x_2 - x_1)\\ &= m_2\ddot{x}_2 - c_2(\dot{x}_1 - \dot{x}_2) - k_1(x_1 + x_2)\end{aligned} \tag{4.13}$$

Since the machine is built after a two degrees of freedom system there is one equation for each mass, this also means that the equations can be split into matrices. Which is easier to use when simulating in computer systems, for the two masses, two spring, two dampers system the following matrices are used:

$$m = \begin{bmatrix} m_{stator} & 0 \\ 0 & m_{piston} \end{bmatrix} \tag{4.14}$$

$$k = \begin{bmatrix} k_{piston} + k_{stator} & -k_{piston} \\ -k_{piston} & k_{piston} \end{bmatrix} \tag{4.15}$$

$$c = \begin{bmatrix} c_{piston} + c_{stator} & -c_{piston} \\ -c_{piston} & c_{piston} \end{bmatrix} \tag{4.16}$$

Resonance in the E-Driver

Resonance in the E-Driver is achieved when the mass of the stator and the piston is moving opposite to each other. This kind of movement is much more efficient, as the masses are working with the electrical force, instead of opposite. One can relate with being on a swing, it is a lot easier to keep a constant pace when you work with the direction of speed. This can be difficult to predict with a theoretical model, since it is hard to estimate how much return force will act on the machine after a strike. It can be done in several ways, one is to attempt to estimate the stiffness of the pole (including soil resistance). This means that the stiffness will vary with the soil composition. Another one is to attempt to estimate the loss of energy in the machine after a strike. The only way to be certain the model is a good approximation is to test the machine and do measurements.

To find the natural frequencies of the system the eigenvalues must be calculated:

$$\big[[k] - \lambda * [m]\big] * \vec{X} = \vec{0} \tag{4.17}$$

Where λ represents the natural frequency and $\vec{X}$ is the positional vector.

When inserting the matrices from equations (4.14), (4.15) and (4.16) into equation (4.17) the following is reached:

$$\begin{bmatrix} (k_{piston} + k_{stator}) - \lambda * m_{stator} & -k_{piston} \\ -k_{piston} & k_{piston} - \lambda * m_{piston} \end{bmatrix} * \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{4.18}$$

When the characteristic equation is applied to the matrice in equation (4.18) this gives:

$$(k_{piston} + k_{stator} - \lambda * m_{stator}) * (k_{piston} - \lambda * m_{piston}) + k_{piston} * (k_{piston} - \lambda * m_{piston}) = 0 \tag{4.19}$$

The characteristic equation will return two lambda values when given inputs, which are the two eigenvalues for the system. The second mode natural 2-DOF frequency can then be found by:

$$f = \frac{\sqrt{\lambda_2}}{2 * \pi} \tag{4.20}$$

4.5 Electric Linear Motor Theory

Typical electric motors are rotational. The development of linear electric motors is still in its infancy, even though the invention is almost a century old. This is because they have generally been considered as ineffective, due to heavy losses from the air gap. However, compared to rotational electric motors they can be cheaper, more stable and quieter. (Boldea & Nasar, 2001)

The electric motor called Resonator is built on the principle that vibrations can be used for something useful. It is therefore built to receive resonance with itself; this causes big vibrations with low input energy. The motor is built from windings and permanent magnets. A big challenge with regards to the electric linear motor is getting adequate impact energy, while keeping the weight requirements. Since the Resonator motor is originally designed to be used in big offshore operations the weight has previously not been an issue. However when it is necessary to carry the motor by hand the weight becomes a critical factor. From international standards the maximum weight of equipment handled by one person shall be 25kg. However this is a bit high for something that is used over a long period of time. The total weight of the post driver shall therefore be less than 20kg.

Eddy Currents

Eddy currents, also called Foucault currents, as the phenomenon was discovered by the french physisist Leon Foucault in 1851. Eddy currents are circular electrical currents, little swirls or “eddies”, that appear within conductors when exposed to a changing magnetic field. For example will relative motion between a permanent magnet and a nearby conductor, as in the case with the post driver, induce eddy currents in the conductor. The eddy current will travel in a closed loop, and according to Lenz´ law, an eddy current will create a magnetic field that opposes the original magnetic field. This means that the eddy currents will contribute to losses in the machine. The magnitude of the current in the eddy loop is proportional to the magnetic field strength, the rate of change of flux and inversely proporsional to the resistivity of the material.

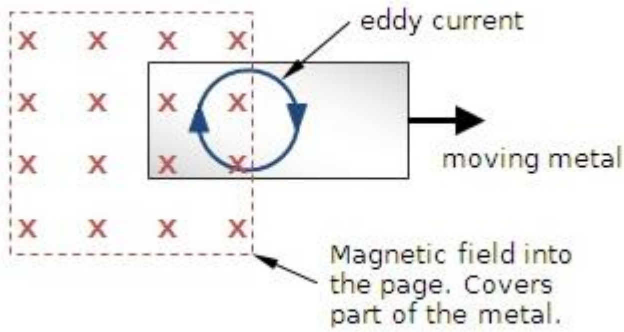


Figure 4.2: Figure showing how eddy currents appear.
Source: http://www.boredofstudies.org

Magnets

More than 2000 years ago the Greeks were aware of a certain type of stone (magnetite) that could attract pieces of iron. Today we call these for magnets, a magnet is a material that creates a magnetic field around itself. Any ferromagnetic material entering this field will experience a force, pulling the object towards the magnet. Other magnets will either be attracted or repelled if entering the magnetic field. (Tipler & Mosca, 2007)

A permanent magnet is an object that is produced from a material that has been magnetized, and produces its own persistent magnetic field. Permanent magnets can be made from materials that are strongly attracted to a magnet, these materials are called ferromagnetic. Some ferromagnetic materials are iron, nickel and some alloys of rare earth metals.

The unit measuring the strength of the magnetic field produced by a magnet is called magnetic flux density and is measured in teslas (Wb/m2).

Gauss´s Law for Magnetism is defined by (Tipler & Mosca, 2007):

$$\phi_{\mathrm{E,net}} = \oint_S \vec{B}_n \, dA = 0 \qquad (4.21)$$

Where $\phi_{\mathrm{E,net}}$ is the electric flux, $\vec{B}_n$ is the component of the magnetic field $\vec{B}$ normal to the surface S at area element dA.

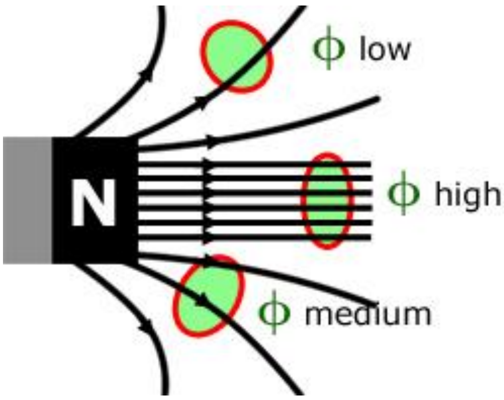


Figure 4.3: Figure explaining magnetic flux density.
Source: http://www.a-levelphysicstutor.com/

For components going normal to the surface S, the **Magnetic flux density** is defined by:

$$B = \frac{\phi}{A} \tag{4.22}$$

Where B is the magnetic flux density, ϕ is the magnetic flux measured in Webers (Wb), and A is the surface area which the flux passes through. The magnetic flux density is then the amount of magnetic flux going through a defined surface.

Magnetic fields can also be produced by an electrical current. These are called **electromagnets** and are usually created by a large number of closely spaced turns, wrapped around an object, so that the magnetic field can run up through the turns and back around like in a regular magnet rod. The strength of the magnetic field created by the electromagnet is proportional to the electrical current in the wires. The main difference between electromagnets and regular magnets is that they can quickly be turned off by switching off the current, and the polarity can be reversed by switching the direction of the current. This creates a lot of different possible applications and is the basis for electric machines. However they require a continuous supply of electrical energy to maintain the magnetic field.

In the post driver, both permanent magnets and electromagnets are used. The piston is built from permanent magnets, while windings are placed outside the piston sylinder. Related to the electric motor of the E-Driver the following equations will be relevant:

Induced Emf per winding turn is defined by:

$$E = -\frac{d\phi}{dt} = -\frac{d\phi}{dt} * \frac{dx}{dt} \tag{4.23}$$

Where E is the induced emf and $d\phi$ is the change in magnetic flux.

Inductance is defined by:

$$L = \frac{\lambda}{I} \tag{4.24}$$

The winding DC resistance is given by:

$$R_{DC} = \frac{p * L}{A_c} \tag{4.25}$$

Where p is the copper resistivity and has a value of 1,72481e-8 Ωm at 20°C, L is the copper wire length, calculated from the average winding diameter.

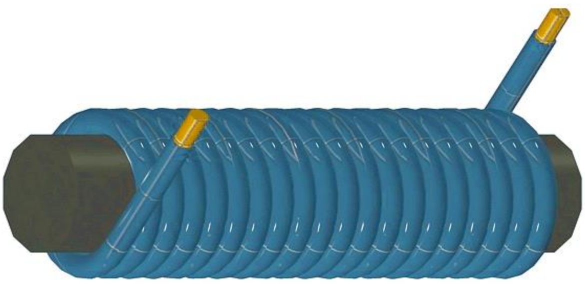


Figure 4.4: Figure of an electromagnet, consisting of electrical coils wrapped around a ferromagnetic sylinder. Source: http://commons.wikimedia.org

The peak current in the machine is given by:

$$I_p = \frac{K_{cu} * A_s * J}{N} \tag{4.26}$$

Where I is the peak current in the coil, A_s is the area of the slot, K_{cu} is the slot fill factor, J is the current density peak and N is the number of turns.

Friction

When two surfaces are in contact and move relative to each other, a tangential force, acting against the motion occurs on both surfaces. This force is referred to as the force of friction. Coulomb (1736-1806) created laws to calculate this friction force, which are still used today. Coulomb also stated that the frictional resistance is greater at the moment just before the two surfaces starts to slide, and so he distinguished between static and kinetic friction. In the E-Driver only the kinetic friction is considered, as not a lot of force is required to start the machine, and from then on it is always moving. Coulomb`s law states:

$$F_f = \mu N \tag{4.27}$$

Where F_f is the tangential frictional force, resisting movement and μ is the coefficient of friction, this constant varies on the material and roughness of the surfaces, N is the normal force, pressing the two surfaces together.

Friction forces are usually unwanted. In such applications the frictional force is a direct loss of energy, and most of the energy becomes heat. This causes a lot of problems in machines, and is one of the main reasons to use lubrication. In the E-Driver this will be the case between the piston tube and the piston, this is a close fit and can lead to big losses if there is a high friction coefficient. The piston must therefore be smeared with grease before it is inserted into the stator.

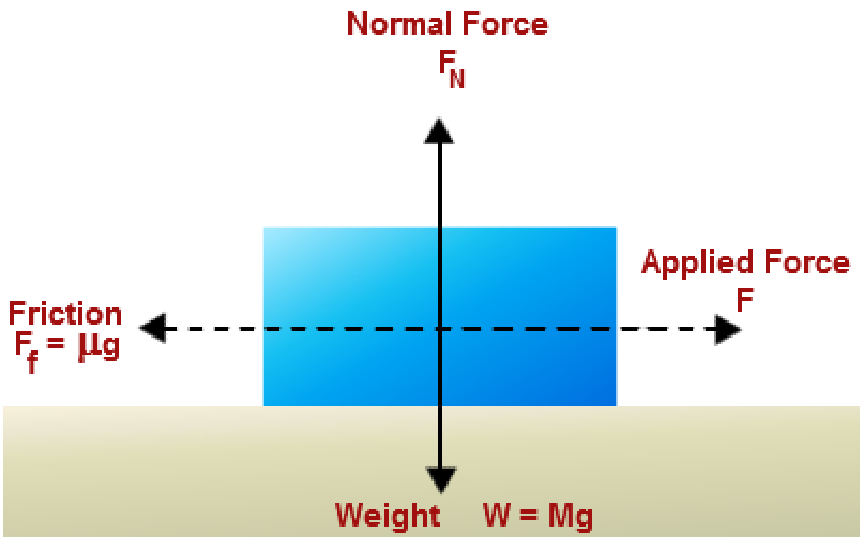


Figure 4.5: Illustration of the friction force. Source: http://images.tutorvista.com/

5 Product Specifications

5.1 Product Goal

To have a clear understanding of the goal and purpose of the concept development, the following product goal has been defined for the E-Driver.

DEVELOP A NOVEL HANDHELD ELECTRIC POST DRIVER THAT IS CHEAP, LIGHTWEIGHT AND EASY TO USE.

The later concept development and weighed screening process will be focused on obtaining this product goal. The three factors in the goal is listed in order of importance, with the product being cheap being the most important factor.

5.2 Important Product Attributes

For the electric post driver to be able to compete with the competitors on the market it needs to be a significant improvement on the current solutions. To achieve this, high priority is placed on the following attributes, in order from most important to least.

1. Mobility, it needs to be light and easy to carry, with as few loose parts as possible.
2. Low production costs.
3. User-friendly design.
4. Safe design with minimal risk of human injury.
5. Durable design

The attribute given most weight is mobility, as this is key to making the post driver into a viable product. Secondly is that it shall be cheap, with low production costs and cheap materials. This is to make it available for everyone. It must also be safe and easy to use, and it must be designed for durability.

5.3 Early Product Specifications

To have an idea of the design limits for the post driver, a table is set up with design limits. These values in Table 5.1 are extrapolated to be able to compete with similar products on the market and from design wishes from Resonator.

Table 5.1: Early product specification for the E-Driver.

Attribute	Limit value
Weight	20kg total
Width (diameter)	400mm
Height	400mm
Minimum running duration	30 minutes
Price	10 000

5.4 Early Cost Estimate

In order to get a rough estimation of what the shelf price for the product can be, an early cost estimate is set up. The numbers in the estimate is collected from information on the web and estimations from Resonator. As they have ordered these types of products quite often, the approximated values are quite good.

Table 5.2: Early cost estimation for the production of the post driver.

Component	Estimated cost (NOK)
Battery	2 000
Aluminum casing	1 000
Plastic parts	500
Permanent magnets	1 000
Springs	600
Electric windings	100
Misc	200
Production cost	2 000
Sum	**7 400**

6 Concept Development

6.1 Functional Analysis of the Product

To optimize the design process the product is split into its sub and base functions, where each function is later reviewed and different solutions are considered.

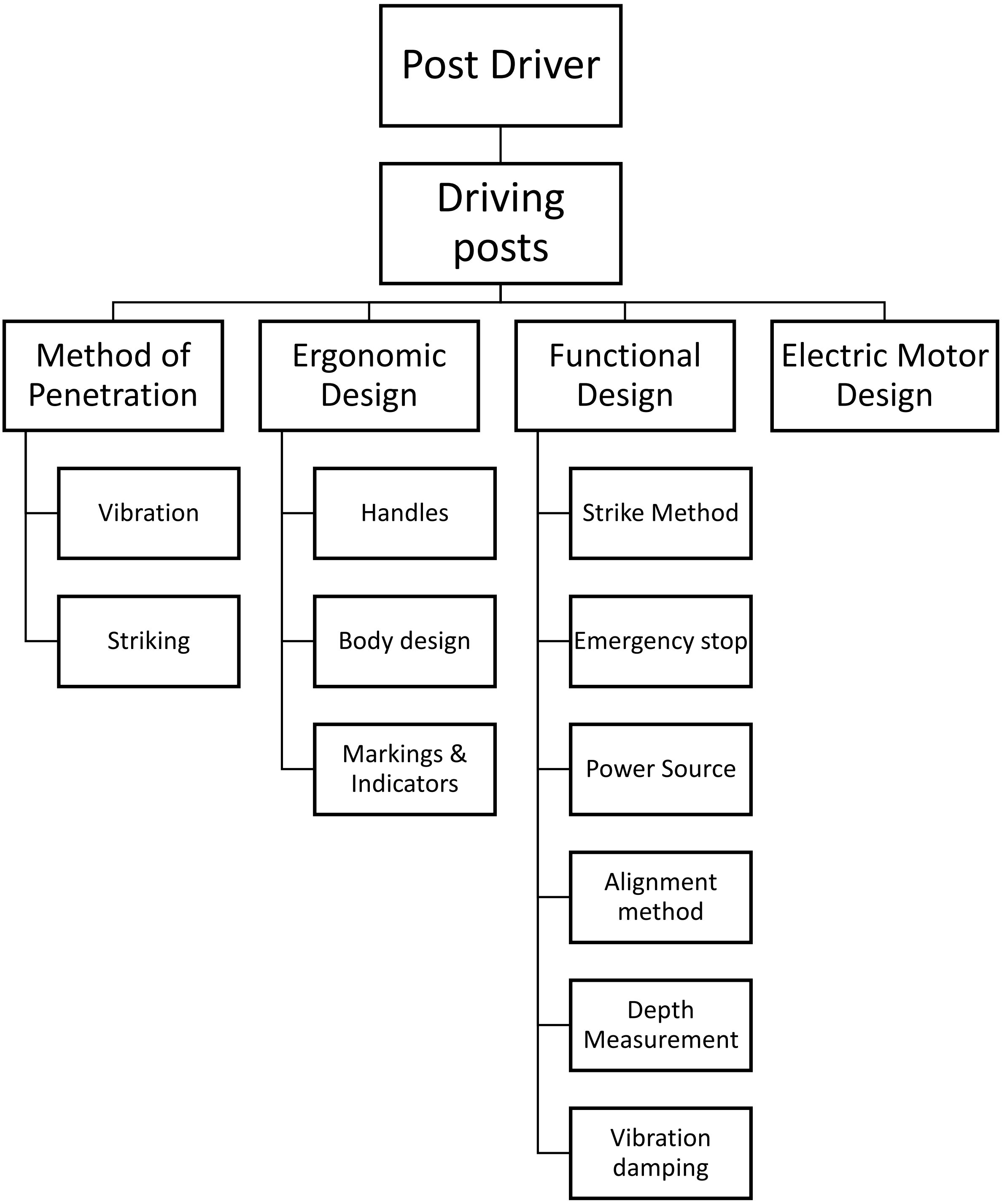


Figure 6.1: Illustration of the product type, first split into its sub functions, and then further into its base functions.

6.2 Method of Penetration

Two methods of driving the post into the earth are considered, one is striking the top of the post, the standard used in the industry today, the other is fastening the product to the post and using vertical vibrations and weight to drive the post.

6.2.1 Weight and vibration

In this method the product is fastened to the post to transfer the vertical vibrations from the post driver to the post. The post driver then also applies a constant weight to the entire system. If the vibrations are strong enough and enough weight is applied these two factors will drive the post into the soil. The vibrations reduce the resistance of the soil and the static force from gravity pushes the post. This principle is often used with structural pile driving, where bigger machines and piles are used. If this principle also can be used for post driving will be dependent on how much weight is required, combined with vibrations, to ensure that the post doesn´t get stuck. Since the E-Driver is handheld it will unlikely be enough static weight to force the post into the soil. Therefore the dynamic model and the first prototype will be based on the striking method.

6.2.2 Striking

This method is more commonly used, and is the same principle as manual operations. A weight is lifted and slammed down repeatedly upon the post to drive it into the soil. Not all of the energy from the blow will be transferred to the post, some will return with the hammer as kinetic energy, as the weight "bounces" away from the post.

6.3 Dynamic model

The first step in developing the post driver is to model the dynamic movement of the driver, as shown in Figure 6.2. A simplistic model for the system is set up in Matlab´s Simulink. This model is based on mechanical springs and damper system with two masses, being the piston and the stator,

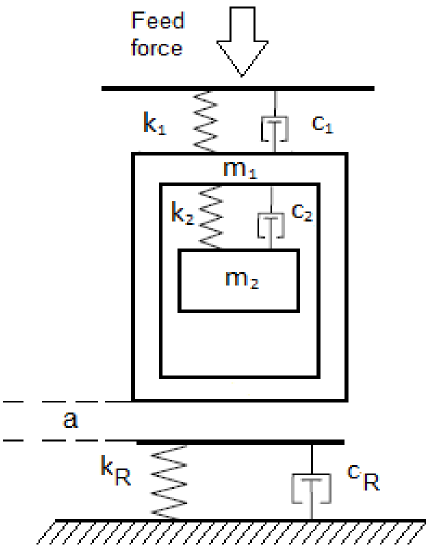


Figure 6.2: Dynamic system of the post driver illustrated, where m_1 is the stator and m_2 is the piston, k1 and c1 is the top spring and damping, k2 and c2 is the internal springs and damping, k_R and c_R is the spring and damping of the post that the stator is striking and a is the air gap. Source: "Resonator impact models and simulations" a Resonator internal document.

and a feed force. The model is used to estimate the strike force that the electric motor is able to strike continuously with.

Factors as the gap between the piston and the post and the reflective energy of the post makes it complicated to get an accurate model of the dynamics, however the model makes it easier to build a functional prototype. This prototype can then be tested, to further improve the dynamics. By finding the actual resonance frequency, measuring actual impact energy and reflective energy etc. the dynamic model can be improved, which again makes it easier to develop a better final product.

The dynamic model is modelled in Simulink, MATLAB. Resonator have already developed models for running their different machines. A Resonator model is therefore studied and modified in order to fit the correct specifications. The main components of the model are illustrated and explained below.

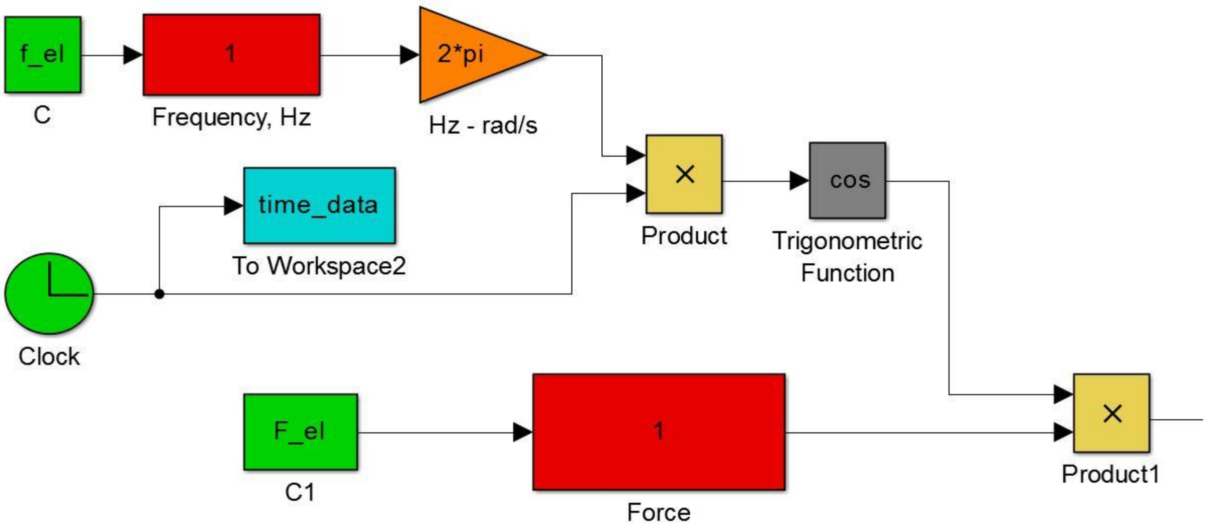


Figure 6.3: An illustration of the modelling of the electrical force in MatLab.

Figure 6.3 is a model of the electrical force, with f_el as input frequency, and F_el as input force. The clock and trigonometric function makes the electrical force into a sinusoidal wave with the electrical force as the amplitude and the electrical frequency as waves per second.

This force is applied to the windings in the electric machine and on the magnets in the piston. The sinusoidal form causes the two masses to move back and forth.

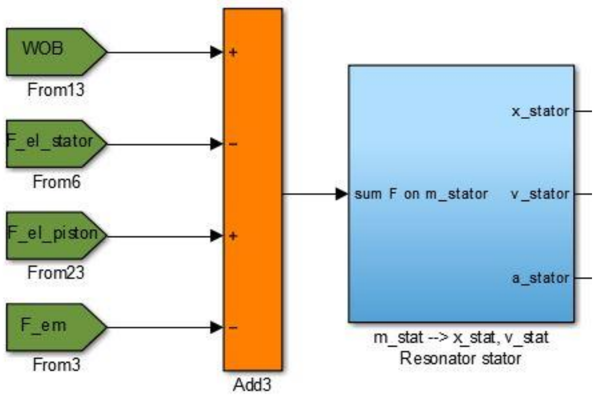


Figure 6.4: Model of the sum of forces acting on the stator.

The part of the model shown in Figure 6.4 uses Newton's second law that the sum of all forces on an object is equal to the acceleration and mass of that object. This law, together with integration is used to calculate the position, speed and acceleration of the stator. This calculation happens within the blue block, and is shown in Figure 6.5.

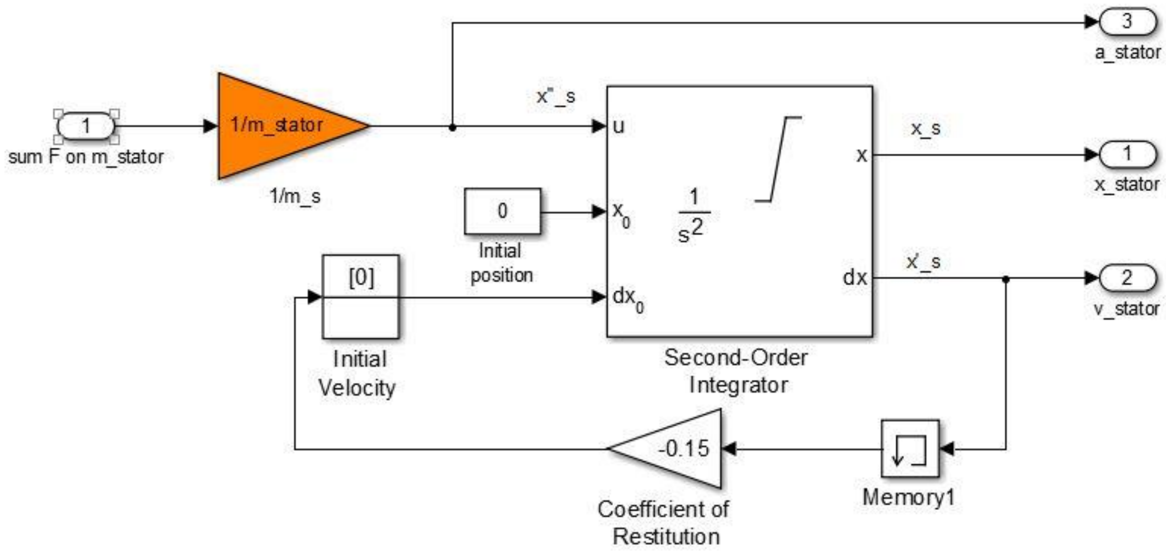


Figure 6.5: Illustrating the details of what happens inside the blue block shown in Figure 6.4: Model of the sum of forces acting on the stator. Gives acceleration, position and speed output.

In this block the position, speed and acceleration is calculated. The acceleration is taken directly from the input, by using Newton's second law. The speed is then calculated by integrating the acceleration once, this speed, multiplied with a coefficient of restitution is then used as the return speed after the strike. The memory block is included to add a one step delay to the initial velocity, to make sure it uses the correct velocity. The position is calculated by integrating the acceleration twice.

The same calculations are done on the piston, except here there is no strike, and the modelling is a bit easier. Only including Newton's second law and two integrations.

These different values that have now been calculated are used to calculate the piston and stator relative position, speed and acceleration compared to each other. This is necessary, as this is input to calculating the total force on the stator.

It is also necessary to include the air gap between the stator and the strike surface, to make sure the model uses the correct speed at impact. It will also affect the resonance frequencies, as the stator will not have a natural movement.

We then have all the parameters that we need in the model, and all that is left is to calculate the impact energy from each impact. Which is simply the loss from the coefficient of restitution. This can be calculated by using the kinetic energy laws and the speed of the stator before and after impact.

$$E_{imp} = \frac{1}{2} m({v_i}^2 - {v_e}^2) \tag{6.1}$$

Where E_{imp} is the impact energy, m is the mass, v_i is the velocity before the strike and v_e is the velocity after the strike.

6.4 Drop Test

The purpose of doing a drop test is to figure out how much force is necessary for the intended action. In this case the intended action is to drive a post into the soil. The vertical force necessary can be calculated by measuring the distance that the pole is driven on each hit, the height that the weight is dropped from and using a specific drop weight. Other factors that are relevant is the shape and diameter of the post. Using different post sizes will make it possible to calculate the difference in penetration force, with regards to the cross sectional area of the post. However only two post sizes are used in the test, this is not enough variation to make any solid connection with cross sectional area and penetration force. To ensure safety while testing protective shoes must be worn at all times during the drop test. A safety chain is also used between the drop weight and the drop release, to make sure the weight cannot fall more than 100mm past the post. This is important at the start of the testing, before the post is standing stable in the soil, to make sure everything doesn't collapse. In this test, impact energy is calculated by disregarding losses, this will give a conservative result, since the impact energy will actually be lower than calculated.

Drop Test Procedure

For the drop test the following method was used.

1. A manual post driver of 10 kg used as drop weight.
2. Different drop heights are used to get different impact energy. Disregarding losses, the impact energy is calculated from equation (4.1): $E = mgh = 10\ kg * 9.81 * height$
   a. Started with a 0.700m drop, which is approx. 70 Joules.
   b. More accurate impact energy of 20 Joules, a 0.2m drop is then used.
3. A stand with a bucket with standard soil composition is prepared, the bucket must at least have a depth of 0.6m and a diameter of 0.4m, this is to achieve conditions of soil movement as close to reality as possible.
4. Soil composition used contains the following components:
   a. A mix of MW, CL and GW soil is used.
   b. One litre of water for every 20 litres of soil.
5. After the bucket is halfway and completely filled the soil is compressed with a weight of 80 kg. The bucket is also compressed after a completed test.
6. Two different posts with standard measurements are used.
   a. Post with 80mm diameter and 85 degrees penetration, blunt end.
   b. Post with 60mm diameter and 70 degrees penetration, blunt end.
7. A beam is installed horizontally 200mm above the bucket with soil; this is used to make markings on the post between each drop.
8. The distance between each marking is measured and recorded.
9. The test is continued for each post, until the post is driven minimum 0.4m into the soil or the penetration has stopped completely.

Drop Test Results

The results from the drop test is listed in the table below, at the bottom an average soil penetration value is calculated. In the average value the first ten results is disregarded, this is to make sure the average value represents the correct penetration speed from when the entire width of the post has penetrated the soil. The goal of the drop test is to investigate if impact energy of approximately 20J is enough to drive the post at a continuous pace.

Table 6.1: Listing the drop test results, for three different tests.

Test with 70J and big pole		Test with 20J and small pole		Test with 20J and big pole			
Drop No.	**Pen. (mm)**	**Drop No.**	**Pen. (mm)**	**Drop No.**	**Pen. (mm)**	**Drop No.**	**Pen. (mm)**
1	47	1	30	1	20	31	3
2	43	2	14	2	19	32	4
3	25	3	10	3	18	33	2
4	25	4	10	4	20	34	3
5	18	5	8	5	15	35	2
6	18	6	6	6	8	36	2
7	17	7	6	7	8	37	3
8	17	8	5	8	6	38	3
9	9	9	4	9	5	39	2
10	10	10	5	10	5	40	2
11	11	11	5	11	4	41	3
12	12	12	5	12	4	42	2
13	16	13	5	13	4	43	2
14	14	14	4	14	4	44	2
15	15	15	4	15	5	45	1
16	5	16	3	16	4	46	2
17	14	17	4	17	3	47	2
18	14	18	4	18	4	48	2
19	11	19	4	19	3	49	2
20	14	20	4	20	3	50	2
21	14	21	4	21	3	51	2
22		22	4	22	2	52	2
23		23	2	23	3	53	2
24		24	2	24	2	54	2
25		25	4	25	3	55	3
26		26	3	26	3	56	2
27		27	3	27	3	57	3
28		28	3	28	3	58	2
29		29	2	29	5	59	3
30		30	3	30	3	60	2
Average pen.	**12.72**	**Avrg. pen.**	**3.6**	**Avrg. pen.**			**2.74**

From the test results it is clear that in this kind of soil composition 20 Joules is enough to drive the post. With the big pole the average continuous penetration was 2.74. This means that if the post driver strikes with 25Hz, which is about 1500 BPM, it will drive the post with a penetration rate of 4.11 meters per minute. The average post is only driven about 0,4m into the soil. This is more speed than is necessary, however in the actual product there will be other losses than may lower the effect.

6.5 Electric Motor Design

The first step in developing a post driver is to design the electric motor that will run it. It needs to have enough power to drive the posts, as well as be light enough to carry by hand. From an electrical standpoint it is recommended to use voltages below 48V, as everything above this is required to follow very strict regulations. This is therefore the upper design limit for the motor. The design of the motor will also influence the functionality and the basic look and feel of the product.

6.5.1 Resonator motors available

Resonator has several motors available, it is also possible to customize one if some different specifications are needed. Motor is chosen from the necessary voltage, power output, size and weight. The available motors can also be modified to achieve new specifications. With the exception of the P2 prototype all the motors below are too heavy, if one of these has to be used, the weight will have to be reduced either by modifications or by changing the material in some components.

Table 6.2: Table showing data for the various electric motors available from Resonator.

Parameters	P6A prototype	P5 prototype	P2B Prototype	P2 prototype
Mass of the Piston	5,5 kg	5,5 kg	8.3 Kg	1.4kg
Mass of the Casing	22kg	20kg	22.9 Kg	3.2 kg
Force capability, F	200N (31 N/A)	300 (12 N/A)	250N (17 N/A)	25-32N (8 N/A)
Voltage / Current	110V / 6.5 A	48V / 25A	220V / 15A	
Length of the active machine	0.21m	0.21m	0.5m	0.040m
Velocity, V	Designed for 5m/s	Designed for 5m/s	Designed for 10m/s	Designed for 4m/s
Diameter	110mm	110mm	80mm	58mm
Phase	1	3	1	1
Stator structure	Slotless	slotted	slotless	Slotless
Designed power level: P = F * V	1 kW*	1.5 kW*	2.5 kW*	100-125 W*
Piston shaft rod	28mm	28mm	10mm	10mm
Magnet inner / outer diameter	28mm / 48mm	28mm / 48mm	10mm / 46.5mm	10mm / 46.5mm
Air gap	2mm	2mm	1.75mm	2,5mm
Stator outer diameter (windings + SMC)	104 mm	104mm	67mm	58mm
Total length	596mm	596mm	940 mm	230mm
Length of piston	210mm	210mm	565 mm	110mm
*Force levels are achieved from the practical testing velocity levels are not reached due to damping. So practical power levels depends on the velocity level				

6.5.2 Functional shape of the electric motor in the E-Driver

In order to achieve the specifications set up in chapter 5.3, different methods of using the available Resonator motors in a post driver design are evaluated. The alternatives below are the different possibilities that have been reviewed. External suggestions from CEO Svein Hestevik from Resonator and Chief Engineer Tore Ensby from NMBU have also been considered.

Alternative 1

The post driver as a complete unit, shaped approximately like a standard manual post driver, placed on top of the post, shown in Figure 6.6. Using aluminium casings and the P5 motor built into the top of the post driver. This is the first alternative considered; seeing as the P5 motor was almost ready to use this would be a very fast solution to test. However the weight was a bit excessive, therefore replacing some steel parts with 7000 aluminium were considered. Since there were few resources in the school workshop an attempt at outsourcing the work was done, however the price for this was more than 25.000 NOK.

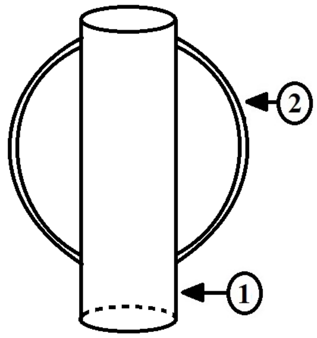


Figure 6.6: New post driver design, where post is inserted from below. 1) Main body, 2) Handles.

Alternative 2

This alternative is a simplification of the first one, where instead of making a new complete product, the P5 motor is attached on the side of a regular post driver as shown in Figure 6.7. This method makes it possible to use a combination of manual and mechanical driving method. As the post can first be driven manually, then the post driver can be attached and further drive the post. Since this method also involves using the P5 motor weight is an issue, however by splitting the driver into different parts more maximum weight is allowed. It will then be necessary to assemble the driver every time a post is to be driven. If the battery is also a separate part it will be three components to assemble.

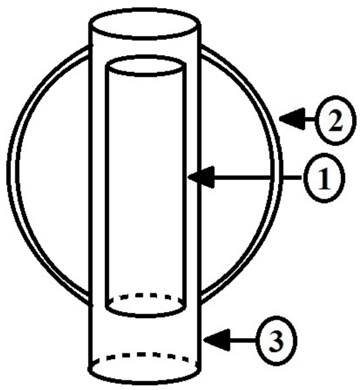


Figure 6.7: Completely enclosed post driver attached to the side of a manual post driver. 1) Electric motor, 2) handles and 3) post driver.

Alternative 3

The post driver as a complete unit, with a new wide motor placed on top of the post as shown in Figure 6.8. This motor is based on the same principles as the P2, which uses mostly plastic materials. This makes the machine very light, and is very efficient. To test this alternative it is necessary to fabricate and assemble all the parts. It is also necessary to order new magnets and SMC rings, as Resonator does not have these on stock for this dimension. The P2 motor is designed for use with much lower forces, so by increasing the force substantially the mechanical strenght aspects must also be considered and evaluated.

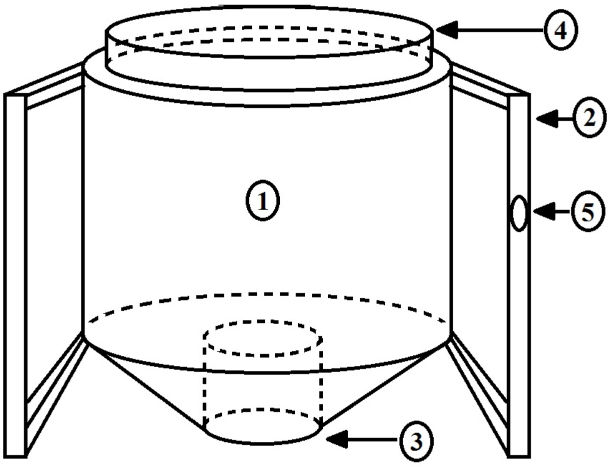


Figure 6.8: Post driver with a wide motor. 1) Electric Motor, 2) handles, 3) mounting hole for the post, 4) battery Pack, 5) emergency stop button.

Alternative 4

Four small synchronized P2 motors are mounted on top of the post, with the driver in the middle. This method gives a good low gravity point, which makes the post driver stable when it is mounted. However it requires fabrication of three additional P2 motors, and a control unit to synchronize the motors. This alternative will give a light and efficient motor.

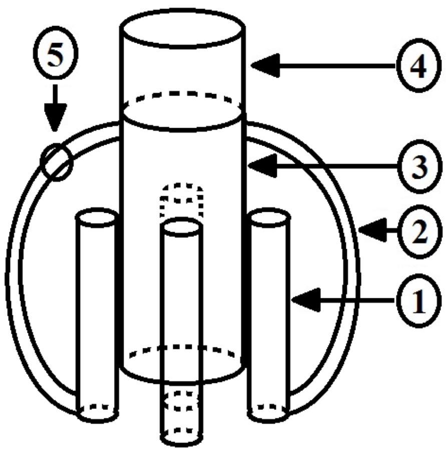


Figure 6.9: Post driver with four small motors. 1) Electric Motor, 2) handles, 3) mounting hole for the post, 4) battery Pack, 5) emergency stop button.

Alternative 5
Using an extended version of the P2 motor as an attachment to a manual post driver. Method will be exactly the same as alternative 2, See Figure 6.7. This is a lightweight alternative, which is also easy to fabricate, as some of the same components as in the P2 motor can be used. However the mechanical strength of the components must also be considered, as the P2 motor is designed for much lower forces.

6.6 Functional Design

All the base functions of the functional design for the post driver, from Figure 6.1, must be evaluated, to ensure that a good solution is used for the final product. These choices will decide the visual design of the post driver, aswell as the human interface.

6.6.1 Strike method

The strike function can be designed in different ways, two methods are evaluated.

Enclosed strike design
This method consists of fabricating a closed outer sylinder, with just a guide at the bottom where the post is fastened by two screws. The stator casing is then striking the inside of the machine. With this method no dirt can come into the machine, and it becomes very solid. It also makes the machine very safe, as no moving parts can be reached from the outside.

Open strike design
With this method the outer casing has a hole in the bottom with a sleeve that the post can be inserted into. The stator casing is then striking directly on the post. The sleeve can also be fastened to the post with two screws. This method is very easy to fabricate, it will also greatly reduce vibrations and noise, as the stator is then only connected to the outer casing by the top spring. This creates a damping function to the outer casing and the handles.

6.6.2 Emergency stop

The post driver shall be designed so it is safe in use and can quickly be turned off. This requires an emergency stop, in case something go wrong. If the operator cannot let go of the handles to operate the emergency stop with full safety, it must be designed so they can be operated without letting go of the handles (Klima- og miljødepartementet; Justis- og beredskapsdepartementet; Arbeids- og sosialdepartementet, 2009). There are several different emergency stop methods frequently used, those that have potential and are considered in this product are listed below:

Emergency stop button
This requires a physical button that can be slammed in if things go wrong. This is a very standard solution on big machines, but not so normal for handheld machines.

Emergency stop wire
This function requires a wire that goes from the machine to the operator, so that if things go wrong the operator can quickly pull on the wire to stop the machine. The wire can also be fastened to the operator, so the machine stops if the operator moves away. This method is normal for machines where you might fall off.

Emergency handhold stop
This method requires that the operator continuously holds down a button in the handhold when operating the machine. As soon as the operator lets go of the handhold the machine will stop. This is

a very efficient emergency stop method for handheld machines, but it requires that the operator constantly holds on to the handle.

6.6.3 Power Source

The power source to the E-Driver is a battery. This battery can be designed in many different ways, it can either be fastened directly to the E-Driver, it can be carried by the operator in a backpack, or it can be a separate unit standing beside the post. The requirement is that it shall last for at least 30 minutes.

Alternative 1

The battery pack built into the product. This method is dependant on a method to fasten the battery to the post driver. It must be easy to connect and disconnect, so that it can be recharged or replaced with another battery.

Table 6.3: Pros and cons for having the battery built into the product.

Pros	Cons
Very mobile product.	Increased total weight of the product
No connections necessary when changing post.	More bulky product

Alternative 2

Battery pack separate from the product and connected via cables. This method is dependant on cables to be connected to the post driver from the battery every time a post is driven. Pros and cons are shown below.

Table 6.4: Pros and cons for having a seperate battery pack.

Pros	Cons
Battery size and weight can be increased.	Less mobile product, two units needs to be moved every time a new post is to be driven.
Product weight per component is reduced.	Cables necessary to be connected for each use.
Smaller parts that are easier to handle.	Two parts instead of one.

Alternative 3

Battery pack carried by the operator. This method requires a battery that is either strapped to the operator in some way or carried in a backpack. This method is more mobile than alternative 2 and it still requires cables to be connected to the post driver, but these do not have to be disconnected and reconnected between every post.

6.6.4 Alignment method

When driving posts it is usually important to have them standing relatively vertically straight. This is an optional function, which can be removed if considered unnecessary or too expensive.

Carpenter´s level

Alignment can be done by including one or several carpenter´s levels

Alignment lines

Alignment lines that can be used for eye measuring can be drawn on the machine.

6.6.5 Depth measurement

After looking at some solutions for depth measurement, this option has been discarded, as this can be quite complicated and expensive. It is also very easy to do with other equipment.

6.6.6 Vibration damping

The machine creates very strong vibrations, this makes it necessary with vibration damping to reduce stress and fatigue on the hands and arms. This method is not evaluated as this function already exists in other post drivers, and have been tested and proved to work. Therefore the same damping method as is used in the handles for the gasoline driven post driver is used in the E-Driver.

6.7 Ergonomic Design

The base functions of the main parts of the ergonomic design must also be considered.

6.7.1 Handle design

The handle design is important in order to get a good ergonomic design that is comfortable to hold over longer periods, as well as carrying and mounting the post driver. The handles must be designed so the machine easily can be turned on and off while maintaining full control (Klima- og miljødepartementet; Justis- og beredskapsdepartementet; Arbeids- og sosialdepartementet, 2009)

Vertical handles

For guiding an object that is in shoulder height, vertical handles are much better suited than horizontal handles. As the operator can hold one handle on each side of the machine and get much better control in all tilting directions.

Horizontal handles

These handles are usually better for carrying heavy objects. The handles can be fastened on the side or on top of the post driver.

Vertical & horizontal handles

By having both vertical and horizontal handles the positive sides of both the other alternatives are achieved. However it increases the production cost by having more handles.

6.7.2 Body design

This is a visual design choice, as the motor must be built in a circular form, any adaptation to another form is mainly for visual purposes.

Circular form

This is the same design form as the electrical motor, and will be the most space efficient solution. However it can be difficult to incorporate the battery design, as no circular battery pack of this dimension is available on the market.

Square form

With a square form on the outer casing it becomes much easier to fasten other components to the product.

Triangular form

With a triangular form on the outer casing it is easy to fasten other components to the sides of the product.

6.7.3 Markings and indicators

It can be necessary with different markings and indicators on the machine. For this product safety markings, battery indicators and power indicators are evaluated. These can be designed and attached in different ways. Some indicators and markings are optional, these will be considered if to be included in the product or not.

Safety markings & usage descriptions fastening method

Safety markings and usage descriptions on products that can cause harm to people or the environment is important in order to ensure safe usage of the product. For the post driver it is very important that the operator does not put any body part inside the area that the post is inserted. The machine must also not be turned on when standing on top of something that can be broken or can move. The vibrations will cause loose objects to jump around and move. These instructions can be fastened in one of the following methods.

Engraved plate

The instructions can be engraved to a steel or plastic plate, then bolted or glued to the machine. This is a very durable solution, which is difficult to remove.

Painted on the machine

This method is flexible, as the paint can be applied anywhere on the machine. It requires that the markings are figures or big letters, as small letters are difficult to paint and read. This method is relatively durable.

Stickers

Stickers with descriptions and instructions are often used in products like this. The solution is not as durable as the other two, however it is very easy to fabricate and gives room for a lot of information to be written on the stickers or to include figures, illustrations and tables with many details.

Usage descriptions

All of the usage descriptions are optional, as these will also be explained thoroughly in the user manual. However some of the descriptions below are considered to be placed on the machine.

Arrow for penetration direction

This is a very simple instruction, to make sure the post driver is used in the correct way.

Frequency dial explanation graph

The purpose of the frequency dial can be difficult to understand, a graph that illustrates what frequency should be used for different soil compositions and degree of moisture. This requires that more extensive testing is done in different soil compositions, and with different amounts of soil moisture.

Power tuning explanation

An illustration showing increasing power when turning the dial right, and an indication of normal power can help the operator to use the E-Driver correctly.

Battery indicators

This is an optional function, the product is fully functioning without it. However it can be a helpful addition that can make the product more user friendly. The battery indicator is dependant on an electrical cable going from the battery to the indicator.

Charging indicator
By having a light that lights up when the battery is charging, and shuts off when fully charged, confusion in regards to whether or not the battery needs to be charged or is fully charged can be avoided. This charging indicator needs to be on the battery charger.
Charging and capacity indicator
With this option it is possible to see how much battery capacity is left, and when the battery needs to be charged. The charging indicator must be on the battery charger, while the capacity indicator must be on the E-Driver.

Power button on/off light
The machine must have a power button, however if this button shall have a light is also an optional function, which can make it easier to see if the product is turned off or not. This can be helpful to avoid unnecessary battery drainage, by reminding the operator that the machine is turned on.

6.8 Durability and Environmental impact

The environmental impact is dependant on the material used in the fabrication of the equipment, however for the post driver the battery is the main contributor to dangerous emissions. The environmental impact is not relevant for the concept screening, as they are same for all solutions. An environmental friendly battery will be chosen if it is compatible with the design solution.

Material selection and surface protection

In order to ensure durability, avoid corrosion and avoid magnetic losses only non-magnetic stainless steels shall be used. Parts exposed to mechanical stresses shall be chosen as SS316, other parts can be aluminum 6063-T4 if necessary to be welded, or if not T6. The company Resonator has already used similar components in SS316 with higher forces and hitting harder objects, therefore no extra mechanical calculations are done to ensure durability of these components. The components that must be in SS316 are the following:

- Stator bolts, as these are exposed to big vibrations and strike force
- Bottom endcap of the stator, as this is striking the post.

Color and painting of components

The machine is split into four parts, the handholds, the display, the casing and the battery. Different, similar or no colors is possible for each part.

7 Concept Screening

In order to select the best design options from the concept development, a concept screening process is used. The process is based on Pugh´s method where important critereas are selected and weighed for each function, with regards to the important product attributes from chapter 5.2 and the product goal from chapter 5.1. These weighed criterias are then used in a selection matrix, where all the criterias are given a score and summed up to indicate which solution is preferable.

7.1 Developing a Selection Matrix

To develop a selection matrix for the concept screening, important criterias with an explanation are listed. These are further developed from the attributes from chapter 5.2. Not all the criterias will be relevant for each base function, only the relevant attributes will be weighed and used to grade the base functions in the concept selection. Product criterias that are used in the concept screening are listed below.

- Rate of penetration – The product is built around driving posts, so the speed at which the posts are driven is very important.
- Durability – The operational lifetime of a product like this sold in Norway is required by Norwegian laws to be minimum 5 years. Excempt is the battery, which has to last for minimum two years (Justis- og beredskapsdepartementet, 2002).
- Mobility – Maximum weight for the whole product is set to 20kg. However the lighter the product, the better for the user. Mobility also includes how easy the product is to carry.
- Efficiency – Minimum operational time for the machine is 30 minutes. Better motor efficiency will give longer operational time per battery capacity.
- Production cost – The cost of producing the E-Driver must be kept as low as possible while the product must still fulfill all safety and design requirements.
- Visual Design – The product design must be appealing in order to attract customers.
- Ergonomic design – Optimizing the solution to fit the operator, to reduce discomfort and fatigue.
- Noise – The noise generated by the machine must be kept to a minimum, as this makes the product more uncomfortable for the user. Daily exposure limits according to Norwegian law is 85 dB and peak value is 130 dB (Arbeids- og sosialdepartementet, 2011).
- Vibration – The vibrations must also be kept to a minimum, as this makes the product more uncomfortable for the user. Daily exposure limits according to Norwegian law for hand and arm vibrations is 5 m/s^2 (Arbeids- og sosialdepartementet, 2011).

7.2 Weighing of Criterias

The weighing of the design criterias splits the selection prosess into the product types sub functions, from Figure 6.1. This is to make sure that only relevant attributes are used to select the design solution for the different base functions and that they are weighed appropriately. The attributes are weighed between 0 and 1, with 1 being most important.

7.2.1 Weighed method of penetration criterias

The method of penetration is critical in order to insure the most efficient method of penetration with the E-Driver. The criterias that are considered important for the penetration method are rate of penetration and durability.

- Rate of penetration – weighed at 1
- Ergonomic design – weighed at 0.5
- Durability – weighed at 0.5

The rate of penetration is considered most important, as this is the main function of the product. the durability is weighed at 0.5, as it is important that the method of penetration does not cause unnecessary stresses on the machine. Ergonomic design is also weighed at 0.5, to ensure a user friendly design is also considered.

7.2.2 Weighed electrical motor design criterias

The criterias considered important for the functional design of the electrical motor are weight, efficiency, durability and production cost. The criterias are weighed below.

- Mobility – weighed at 1
  The mobility of the motor is weighed at maximum, since the motor design is the part of the E-Driver where most of the weight can be reduced, this is the most critical criteria.

- Production cost – weighed at 0.8
  This criteria is weighed second highest, since the motor also consists of the highest cost in the E-Driver and it is important to keep the cost low to be able to compete in the market.

- Durability – weighed at 0.6
  The durability must be good enough that the lifetime of the E-Driver is minimum 5 years, however it must also be able to withstand some rough treatment. If it is easy to damage or break it will create unhappy customers and complaints, which is bad for marketing.

- Efficiency – weighed at 0.4
  Weighed low, as long as the operational time of the motor is within the requirements a higher efficiency is not necessary. However higher efficiency can reduce battery size, or increase operational time.

- Visual & ergonomic design – weighed at 0.4
  Both visual and ergonomic design are weighed at 0.4.

7.2.3 Weighed functional design criterias

The functional design is the sub function with most design options, not all the criterias listed will be relevant for each base function, only the relevant attributes for each base function will be used in the concept selection. Criterias are weighed and listed below.

Strike method criterias

- Noise – weighed at 0.8
- Vibration – weighed at 0.6
- Durability – weighed at 0.5
- Production cost – weighed at 1
- Ergonomic design – weighed at 0.8

Emergency stop criterias

- Ergonomic design – weighed at 1
- Production cost – weighed at 0.6

The ergonomic design of the emergency stop is how easy and quickly the user can stop the machine, this is main function of the emergency stop and is weighed at 1. The production cost for the emergency stop is not that high so it is weighed at 0.6.

Power source

- Mobility – weighed at 1
- Production cost – weighed at 0.6
- Ergonomic design – weighed at 0.8

The efficiency and weight are equally important, the production cost aspect is not weighed as high on the power source, as a low quality battery will have a much shorter lifetime than one of high quality.

Alignment method

- Production cost - weighed at 1
- Ergonomic design – weighed at 0.8

7.2.4 Weighed ergonomic design criterias

The ergonomic design functions are weighed in the same way. With production cost being the most important criteria. But, there are two design criterias, so design can trump production cost.

Handle design, body design, markings and descriptions

- Visual design – weighed at 0.7
- Production cost – weighed at 1
- Ergonomic design – weighed at 0.7

7.3 Concept Selection

In the concept selection the design solutions presented in chapter 6 Concept Development, are selected through pugh´s method. The solutions are scored on weighed attributes, which are then summed up to select the best option. The functions are given a score from 1 to 5. The highest scoring design solutions are chosen for the final design.

The formula used to calculate the best solution is defined as:

$$Total\ score = \sum(score * weighing) \quad (7.1)$$

7.3.1 Method of penetration selection

The method of penetration decides the basic principle behind the penetration of soil. Since the weight and vibration method has not been tested for this type of product, with low weight and no downwards force, the rate of penetration cannot be compared. This should be further tested when a fully functioning prototype is made. The method of penetration is selected according to the table below.

Table 7.1: Selection matrix for the method of penetration.

Criteria	Weighing	Weight and vibration	Striking
Rate of penetration	1.0	0	0
Ergonomic design	0.5	2	5
Durability	0.5	3	4
Sum weighed score		**2.5**	**4.5**

From Table 7.1 the highest scoring solution is the striking method. This is mostly because of the ergonomic design, which it scores higher since it does not require to be fastened and unfastened between each driven post. It also scores higher on durability since it requires fewer components.

Selected method of penetration is the striking method.

7.3.2 Electric motor design selection

To select the functional design of the product weighted design criterias are made. These are used to quantify and summarize the different aspects of the various shapes to make sure the best shape is selected.

Table 7.2: Selection matrix for the electric motor design, with 5 alternatives.

Criteria	Weighing	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5
Mobility	1.0	2	1	5	5	4
Production cost	0.8	1	3	5	3	5
Durability	0.6	5	3	3	3	3
Efficiency	0.4	5	3	4	4	4
Visual design	0.4	5	3	4	3	4
Ergonomic design	0.4	3	1	5	3	1
Sum weighed score		24.6	17.6	29.6	24.6	24.6

Table 7.2 clearly shows that alternative 3 scores highest overall and is the preferred solution.

- Alternative 1 scores poorly on the first two criteria's, because of high weight and expensive production costs of aluminium parts.
- Alternative 2 scores poorly overall because it is made up of heavy separate components that needs to be fastened and disassembled for every pole driven, the parts also needs to be connected with cables. This gives a poor design solution.
- Alternative 3 scores very well on mobility, production cost and design. This is because of light plastic components used in the motor. However it is not as durable as metals.
- Alternative 4 scores pretty well, but it is more complicated in production when making four separate motors, then assembling them into one unit. It also makes it harder to replace parts later.
- Alternative 5 scores well on mobility and production costs, since it is made from light plastic materials, however the same issues as with alternative 2, with several components arise in this solution.

Selected solution is alternative 3, the post driver as a complete unit with a new wide motor.

7.3.3 Functional design selection

The different solutions for the base functions of the functional design that are described in chapter 6.6 are graded, and the best solution is selected, based on the weighed criterias set up in chapter 7.2.3.

SELECTION OF STRIKE METHOD

Table 7.3: Selection matrix for the strike method.

Criteria	Weighing	Enclosed strike design	Open strike design
Noise	0.8	2	4
Vibration	0.6	1	5
Durability	0.6	5	3
Production cost	1	5	4
Ergonomic design	0.8	4	5
Sum weighed score		20.8	24.8

From Table 7.3, the selected solution is open strike design.

- Open strike design scores higher on noise as it will be striking on wood not metal.
- It scores well on the vibration criteria as the outer casing will not be involved in the striking process, only connected by a spring. This greatly reduces vibrations.
- It scores less on durability, as with an open design dirt can enter the outer casing.
- It scores less on production cost as an additional hole must be machined in the bottom.
- It scores higher on the ergonomic design, as it will be more stable on the post, as the post can be pushed futher into the machine.

SELECTION OF EMERGENCY STOP

Table 7.4: Selection matrix for the emergency stop.

Criteria	Weighing	Emergency stop button	Emergency stop wire	Emergency handhold stop
Ergonomic design	1	2	3	5
Production cost	0.6	4	4	2
Sum weighed score		4.4	5.4	6.2

From Table 7.4 the Selected solution is to use an emergency handhold stop

SELECTION OF POWER SOURCE

Table 7.5: Selection matrix for the power source.

Criteria	Weighing	Alt. 1	Alt. 2	Alt. 3
Mobility	1	4	2	4
Production cost	0.6	3	5	4
Ergonomic design	0.8	5	1	3
Sum weighed score		9.8	5.8	8.8

From Table 7.5 the selected solution is to use alternative 1, to have the battery built into the post driver. This solution requires that the total weight of the product is less than 20 kg.

Table 7.6: Selection matrix for the alignment method

Criteria	Weighing	Carpenter´s level	Alignment lines
Production cost	1	3	5
Ergonomic design	0.8	5	2
Sum weighed score		**7**	**6.6**

From Table 7.6 the selected solution is to use a carpenter´s level for the alignment.

7.3.4 Ergonomic design selection

The different solutions for the base functions of the ergonomic design that are described in chapter 6.7 are graded, and the best solution is selected, based on the weighed criterias set up in chapter 7.2.4.

SELECTION OF THE HANDLE DESIGN

Table 7.7: Selection matrix for the handle design

Criteria	Weighing	Vertical handles	Horizontal handles	Vertical & horizontal handles
Visual design	0.8	5	3	4
Production cost	1	4	5	3
Ergonomic design	0.8	1	2	5
Sum weighed score		**8.8**	**9**	**10.2**

Using both vertical and horizontal handles scored much higher on ergonomic design, since it can then easily be both lifted vertically and carried, and it can be guided and controlled when the E-Driver is standing on the post at face height.

From Table 7.7 the Selected solution is both vertical and horizontal handles.

SELECTION OF THE BODY DESIGN

Table 7.8: Selection matrix for the body design

Criteria	Weighing	Circular form	Square form	Triangular form
Visual design	0.8	5	3	4
Production cost	1	5	3	2
Ergonomic design	0.8	5	4	3
Sum weighed score		**13**	**8.6**	**7.6**

From Table 7.8 the selected solution is circular form.

SELECTION OF MARKINGS AND INDICATORS

For this selection matrix, the different options are all included in the same Table 7.9. For the selection of usage descriptions, battery indicators and the power on/off light a minimums score of 10 is used as the deciding factor. If the option scores more than 10 points it is considered important enough to include in the design, if not it is discarded.

Table 7.9: Selection matrix for the markings and indicators.

Safety markings & usage description fastening method				
Criteria	**Weighing**	**Engraved plate**	**Painted on**	**Stickers**
Visual design	0.8	5	3	4
Production cost	1	2	3	5
Ergonomic design	0.8	4	3	5
Sum weighed score		**9.2**	**7.8**	**12.2**

Usage descriptions				
Criteria	**Weighing**	**Directional arrow**	**Frequency tuning graph**	**Power tuning explanation**
Visual design	0.8	3	5	4
Production cost	1	5	4	5
Ergonomic design	0.8	3	5	4
Sum weighed score		**9.8**	**12**	**11.4**

Battery indicators			
Criteria	**Weighing**	**Charging indicator**	**Charging and capacity indicator**
Visual design	0.8	3	5
Production cost	1	5	3
Ergonomic design	0.8	3	5
Sum weighed score		**9.8**	**11**

Power button on/off light		
Criteria	**Weighing**	**Score**
Visual design	0.8	4
Production cost	1	3
Ergonomic design	0.8	2
Sum weighed score		**7.8**

From Table 7.9 the sticker solution has been chosen for the markings and descriptions. This is because it is cheap, and can contain a lot of information.

The usage descriptions that will be included in the solution, as they scored higher than 10 is:

- ***Frequency tuning graph***
- ***Power tuning explanation***

For the battery both charging and a capacity indicator will be included in the design.

A power button on/off light will not be included in the design.

7.3.5 Selected design

The final design will consist of the following solutions:

- Method of penetration: Striking.
- New wide electric motor will be designed and it will be incorporated into the post driver.
- Strike method will be open strike design.
- The emergency stop will be built into the handle.
- The battery will be attached to the post driver.
- The post driver will be aligned by a carpenter´s level.

- The handles will be fitted with vibration dampers.
- The E-Driver will be fitted with both horizontal and vertical handles.
- The outer casing will be of a circular design.
- Safety markings and usage descriptions will be made of stickers.
- The E-Driver will be marked with graphical descriptions for the vibration and power tuning.
- A battery capacity indicator will be on the E-Driver, and a charging indicator on the charger.

8 Prototype Development and Testing

The goal for the prototyping and testing is to test if the motor design will function as intended, to verify the accuracy of the dynamic model and to measure an estimated penetration rate for the E-Driver.

However because of long order time for the parts necessary it is not possible to fabricate this alternative in the given time frame. This is solved by instead fabricating the motor in alternative 5, since the parts necessary to be ordered is then already available. Then using it as intended with alternative 3. The difference in the motors is only in either extending the P2 in vertical or horizontal direction, it will not affect the functionality of the motor, as long as it is driving the post as intended with alternative 3. This prototype will then be tested and if successful a final concept with alternative 3 will be designed.

8.1 Prototype Fabrication

The prototype will be built with a functional design in mind, as it is not going to be used for anything other than testing. The motor design will be the same as 2B, but the design will be extended, therefore only simple construction drawings are made before fabrication. The components necessary to fabricate, to assemble the prototype are the following:

- Piston tube, in plastic.
- 4 x Winding spacers outside of piston tube, in plastic.
- 2 x End cap winding spacers outside of piston tube, in plastic.
- Piston rod in non-magnetic steel.
- 2 x End caps, in non-magnetic steel.
- 1 x Fixing end cap
- 14 x “SMC” rings
- Outer casing
- 4 x long 8mm bolts
- Spring spacer

These components are available and do not need modification:

- 5 x Magnets (Ø46.5, Øi10, 40).
- 6 x Magnet spacers (Ø46.5, Øi10, 10).
- 2 x “big springs”
- 4 x “small springs”
- Test pipe in plastic or steel.

8.1.1 Fabrication and assembly of the stator

The first part in fabricating the prototype is making the stator. The main part of the stator is the piston tube, which must be made from a solid plastic material. For this prototype POM plastic was chosen. A tube with diameter 60x40mm and 1m length was purchased. This tube was then machined from both sides in order to make it fit the magnets in stock. These have a diameter of 48mm. The tube was therefore made with an inner diameter of 48.5mm and an outer diameter of

52.5mm. The piston rod from the 2B machine was then trial fitted to ensure a good fit. The tube was then cut to the length l_s calculated below.

$$l_s = 6 * windings + 5 * spacers + 2 * spring\ chambers \quad (8.1)$$

By entering the data from the prototype design, the following tube length was calculated.

$$l_s = 6 * 36 + 5 * 14 + 2 * 50 = 386mm \quad (8.2)$$

Next step was machining the winding spacers, which shall fit outside the piston tube. These must be made with a very tight fit, to ensure they do not move during the winding process. These were machined from a Nylon tube, since they have no mechanical purpose. The spacers were made with an inner diameter of 52mm and an outer diameter of 62mm. A 10mm wide, 2.5mm deep groove is also machined, to allow the windings to move from one section to the other. These were then fitted in place on the piston tube. The spacers are fitted so that the SMC rings are resting on the edges and not on the windings. The SMC rings are 25mm in length. First spacer is fitted at 86mm on the piston tube, then the next spacer at every 36mm.

Next step is machining the end cap winding spacers. These are made from a solid bolt with an outer diameter of 80mm. The endcaps are machined with an inner diameter of 52mm, to be able to fit on the piston tube. The outer diameter of the endcap is 62mm for the first 32mm, for fitting the SMC rings, and then 70mm on the rest 18mm in order to match the outer diameter of the SMC rings. A groove is also machined, to make sure it is room for entry and exit of the winding cable. The end caps are then fitted on the piston tube.

Figure 8.1: Assembled stator, with winding spacers, endcap winding spacers and windings installed. Some windings are left unprotected for illustration purposes.

Now that all the spacers have been fitted the stator is ready for the windings to be installed. This was done in a turnery. The stator were mounted so it could spin easily, a stand with the winding coil were set up next to the turnery. The turnery was then spun and the winding coil guided to fit onto the piston tube. Every other winding must be winded in opposite direction, to ensure that the force acts in the same direction on the magnets. Since the windings were done with 2mm wire, in 2 layers only it was not possible to wind one winding chamber at a time. This would cause the wire to end up on the wrong side when winding forth and then back again to the starting position. To resolve this the entire length of the machine were first winded once, and then back again. See picture below for result. To fasten the windings electrical tape is used in between some chambers. The SMC rings are then threaded on the outside of the windings. The inner diameter must be machined to fit on the outside of the windings. It is important not to damage the windings, so the fit cannot be tight.

8.1.2 Fabrication and assembly of the piston rod

First step in building the piston rod is calculating the length l_p of the rod. See calculation below:

$$l_p = 5 * magnets + 6 * spacers + extra\ space \tag{8.3}$$

By entering the data from the prototype design, the following piston rod length was calculated.

$$l_p = 5 * 40 + 6 * 10 + 60 = 320mm \tag{8.4}$$

The hole in the magnets and magnet spacers is 10mm, a rod if this dimension is therefore chosen in non-magnetic stainless steel, of type SS316. The rod is cut and threaded 40mm on both sides. One normal nut, and one locking nut is used to lock the magnets in place. The normal nut is first fastened, and then secured with a locking nut outside. This is to simplify the installation of the magnets. The magnets must be installed with equal poles towards each other, and a spacer in between, this requires a lot of force to push the magnets together.

8.1.3 Fabrication of the end caps

The end caps must be made with a groove to fit both the stator and the spring. Also four boltholes near the outer end must be machined, to be able to tighten the end caps onto the stator. The dimensions used are:

- 120mm thick end caps.
- Ø96mm diameter end caps (to ensure fit in 100mm pipe),
- Ø70mm stator groove diameter (1mm deep groove)
- Ø45.5mm outer spring diameter (3mm groove)
- Ø32mm inner spring diameter (0mm groove)
- 4 x M8 boltholes made at centre lines at Ø84mm.

8.1.4 Spring spacers

The spring spacers are controlling the amplitude of the piston. Without any spring spacers there is no pre-compression of the springs when assembled. Without the pre-compression one spring will not be active. When the springs are precompressed the stiffness of the system is doubled. By using a 10mm spacer on each side, both springs are compressed 10mm, and the amplitude must then be lower than 10mm. The spring spacers must be fabricated from a hard plastic material, in this case POM is used. They are made small enough to fit inside the piston tube, but big enough to have the entirety of the spring resting on the surface.

8.1.5 Top spring with weight

The purpose of the top spring with weight is to act as a driving force on the stator, keeping it from jumping up from the pole. For the prototype a round sylinder is used as the weight, but in the final machine, the battery and outer casing will act as the weight.

A spring with an approximated spring constant of k=14kN/m is used. This spring is welded to the top end cap on the stator, then another end cap with same dimensions is welded to the top of the spring. On top of this end cap a steel sylinder weighing 8.6kg is welded, to act as a driving mass on top of the spring. The spring must be spot welded with more than 4 spots, otherwise the strain on one spot can become too high.

Figure 8.2: Picture of the spring welded between the stator and the top end with mass.

8.1.6 Assembly

Before assembling all the finished parts, the first step is making sure that the stator is not short circuiting on the SMC rings and will be electrifying the entire unit. This is done using a megger insulation test. One cable is fastened to the wire from the windings, and one is fastened directly to the SMC rings. It is then tested with 1kV. If any current is detected there is a short circuit somewhere between the windings and the SMC rings. This can be corrected by removing the SMC rings, looking for scratches on the windings, and if discovered, covering them with electrical tape. The SMC rings are then replaced, and the megger test must be re-done, to make sure the error has been corrected.

The long bolts can now be prepared. One locking nut is placed on the bottom end of each rod, at approximately 50mm. Then one end cap is threaded onto the top end of the bolts. This makes the basis for the assembly; it is then placed with the bottom of the bolts on the floor, with the locking nuts securing the end cap in place.

Now one 10mm spring spacer plus one spring is placed in the spring groove on the end cap. The stator is then placed on top of the spring and spring spacer, into the stator groove in the end cap.

Non-magnetic grease that can withstand high temperatures must now be applied to the piston rod. The rod can then be inserted into the stator; this will cause it to get stuck, because the magnets are attracted to the SMC rings, and the spring in the bottom.

The piston rod must be forced to the bottom of the tube. Then the second spring and spring spacer is inserted into the stator, and lastly the second end cap is threaded onto the long bolts, with the grooves facing down towards the stator. Once the compression of the spring starts the end cap is fastened with minimum two nuts in opposite corners. It is now important to make sure that the spring spacer fits inside the stator properly as the top end cap is further compressing the springs and the nuts tightened.

When the spring spacer is fitted inside the stator and the springs are starting to be compressed all SMC rings must be properly aligned, and it must be verified that the stator is fitted inside the grooves on both end caps.

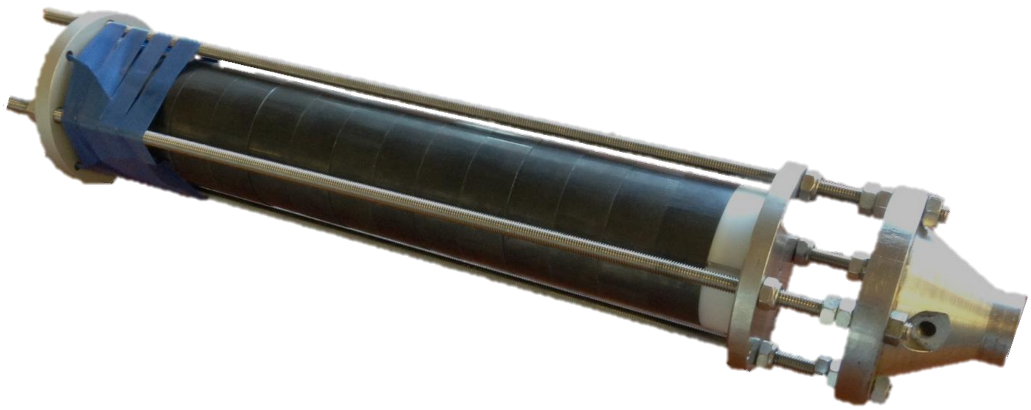


Figure 8.3: Picture showing the finished assembly of stator with SMC rings, piston, end caps and striking head. Wires are taped over for protection.

Now the top end cap can be tightened properly with four nuts, until there are no clearings between either the end cap and stator or any SMC ring.

After assembly the megger insulation test must be redone, to see if there is any short circuit between the windings and the bolts or end caps.

Table 8.1: Finished prototype specifications, to be used in the Matlab dynamic simulation.

Parameters	Value
Electrical force at design speed	F_el = 200N
Total weight of top spring with weight	m_feed = 8.5 kg
Feed force, from top spring with weight	F_feed = 83.4 N
Total weight of piston:	m_p =
Total weight of Stator:	m_s =
Total weight of machine:	m_tot
Inner spring constant	k_i = 32 * 2 = 64 kN/m
Outer spring constant	k_o = 14 kN/m

8.2 Prototype Testing

The goal of the prototype testing is to verify that the E-Driver prototype is functioning properly and that it can drive a post in the bucket of soil used in the drop test. From the data recorded from the test a rate of penetration will be estimated and later compared to the value from the drop test. This comparison can also be used to check the accuracy of the dynamic model. If the impact energy is different in the post driving test than in the drop test, it indicates that the actual impact energy is not the same as estimated in the dynamic model.

When using the prototype specifications from Table 8.2 in the model, an optimized electrical frequency can be found. This frequency will be a bit lower than the free 2-DOF resonance frequency, as there will be some damping from the air in the piston sylinder. The real resonance frequency will be even higher, as the model is simplified with a locked top spring. Impact energy is also estimated.

Table 8.2: Estimated data from the dynamic model in Matlab.

Data input	**Value**
Free 2-DOF resonance frequency	26.46 Hz
Optimized electrical resonance frequency	25 Hz
Estimated impact energy	20.4 J
Number of impact(s) each electrical cycle	0.7

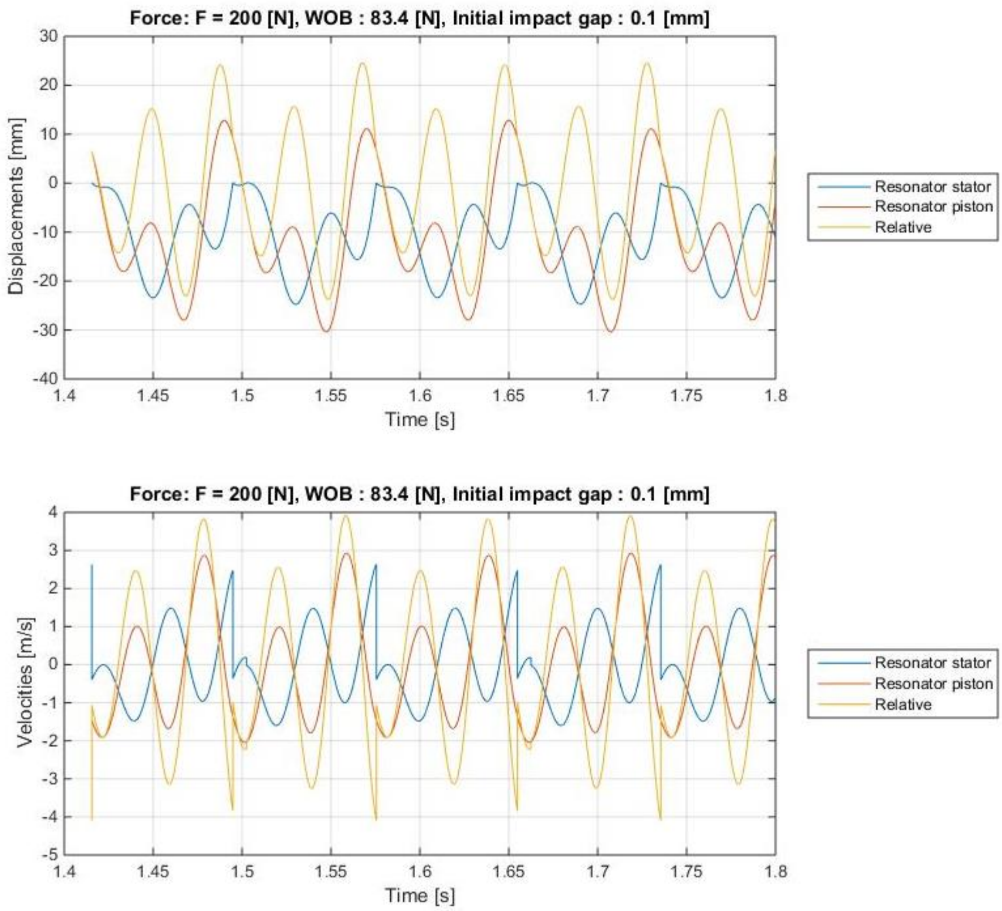


Figure 8.4: Illustrations of the dynamic velocity and displacement of the post driver, after it has stabilized. As the piston and stator are moving in opposite synchronization in the velocity figure, the movement is in resonance.

Test environment
The testing shall be done in an enclosed and safe environment that cannot be accessed during testing. Control and monitoring of the machine shall be done from outside of the enclosure. A video camera placed inside the enclosure will be used to monitor the testing.

Rigging of the machine
The machine must be secured, with only vertical motion possible, inside an enclosure. This is to prevent it from falling or tilting during testing. This will give both friction and incorrect test results.

Bucket of soil
The bucket of soil used shall be the same as described in the drop test, the same soil composition and packing method is also used. This is to ensure consistency between the results.

Testing
The testing is split into two parts. The first part is the electrical testing, where the machine is placed inside a test stand and different voltage and frequencies are run. The second part consists of a real post driving test, where the machine is used to drive a post into a test bucket of soil.

Measuring equipment
Resonator has the following available measuring equipment for the prototype testing:

- Position LVDT (Linear variable differential transformer), used for measuring linear displacement
- Accelerometer, a device that measures proper acceleration.
- Load cell, a transducer that converts force into a measurable electrical output.
- Strain gauge, a device that uses deformation and electrical conductance to measure strain.

ALL interaction with the machine inside the enclosure shall only be done when the power source is fully turned off or disconnected.

8.2.1 Risk assessment
To be able to use Resonator facility their HSE procedures must be followed, that entails performing a risk assessment for the testing, to measure how big a risk the test is, and if any additional safety precautions must be followed. The risk analysis must be approved and signed by Resonator´s responsible HSE manager. The filled in Risk Analysis sheet is shown below, the sheet was signed and approved by Resonator.

Figure 8.5: Finished prototype, ready to be tested.

Unit: **Date: 07.04.2015**
Responsible: Svein Hestevik
Participants in the risk assessment (including their function): Anders Omvang, student

Activity from the identification process form	**Potential undesirable incident/strain**	**Likelihood:**	**Consequence:**			**Risk value**	**Comments/status Suggested measures**
		Likelihood (1-5)	Human (A-E)	Environment (A-E)	Economy/ material (A-E)		
Electrical fault, overload or short circuit.	Will force the machine to shut down, and wires to be replaced.	1	A	A	B	1B	Control system has a fuse, machine to be properly isolated before testing. Testing to be done in an enclosed area.
Parts coming loose from vibration.	Machine damage or shutdown.	1	A	A	B	1B	Tighten everything properly.
Loud noise from running the machine	Ear damage	1	A	A	A	1A	Use hearing protection
Striking the post.	Squeezing fingers between post and the machine.	1	C	A	A	1C	Do not place fingers between the strike surface and the machine. Testing to be done in an enclosed area.
Vibration	If machine is held while running, vibrations can cause health issues.	1	C	A	A	1C	Do not hold the machine while it is running. Testing to be done in an enclosed area.
Welded spring breaking	Will cause the top spring end cap with weight to become loose.	3	A	A	A	3A	Treat spring carefully, avoid damage or unnecessary strain.

Likelihood, e.g.:
1. *Minimal*
2. *Low*
3. *Medium*
4. *High*
5. *Very high*

Consequence, e.g.:
A. *Safe*
B. *Relatively safe*
C. *Dangerous*
D. *Critical*
E. *Very critical*

Risk value (each one to be estimated separately):
Human = Likelihood x Human Consequence
Environmental = Likelihood x Environmental consequence
Financial/material = Likelihood x Consequence for Economy/materiel

Potential undesirable incident/strain

Identify possible incidents and conditions that may lead to situations that pose a hazard to people, the environment and any materiel/equipment involved.

Criteria for the assessment of likelihood and consequence in relation to fieldwork

Each activity is assessed according to a worst-case scenario. Likelihood and consequence are to be assessed separately for each potential undesirable incident. Before starting on the quantification, the participants should agree what they understand by the assessment criteria:

Likelihood

Minimal 1	Low 2	Medium 3	High 4	Very high 5
Once a year or less	Once every 6 month or less	Once every 3 month or less	Once a month or less	Once a week

Consequence

Grading	Human	Environment	Financial/material
E Very critical	May produce fatality/ies	Very prolonged, non-reversible damage	Shutdown of work >1 year.
D Critical	Permanent injury, may produce serious health damage/sickness	Prolonged damage. Long recovery time.	Shutdown of work 0.5-1 year.
C Dangerous	Serious personal injury	Minor damage. Long recovery time	Shutdown of work < 1 month
B Relatively safe	Injury that requires medical treatment	Minor damage. Short recovery time	Shutdown of work < 1week
A Safe	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day

The unit makes its own decision as to whether opting to fill in or not consequences for economy/materiel, for example if the unit is going to use particularly valuable equipment. It is up to the individual unit to choose the assessment criteria for this column.

Risk = Likelihood x Consequence

Please calculate the risk value for “Human”, “Environment” and, if chosen, “Economy/materiel”, separately.

About the column ”Comments/status, suggested preventative and corrective measures”:

Measures can impact on both likelihood and consequences. Prioritise measures that can prevent the incident from occurring; in other words, likelihood-reducing measures are to be prioritised above greater emergency preparedness, i.e. consequence-reducing measures.

8.2.2 Electrical test

In the electrical test, the machine was rigged into a simple tube that kept it in place, resting upon a metal surface. This makes it easy to run the machine and attempt to reach the design voltage without exceeding the current limit for the wires, a RMS value of 20A. The resonance frequency is found by varying the frequency while raising the voltage. The closer to resonance the machine is operating, the less current is needed by the power supply. The resonance frequency will also vary, depending on the material properties of what the machine is striking, and if the object being struck is moving or not. To make sure that the windings do not overload. The machine is connected to a DC supply, and started off on 25V, then the voltage is gradually increased up to 40V. The design voltage is 48V, but some losses is to be expected. The current in the wires can be measured in real time, so the progress can be watched closely. If the piston does not reach the design speed relative to the stator and the voltage is set to 48V the wires can be overloaded and damaged. If the machine is not running at design speed, this can be caused by too tight a fit in the piston tube, lack of grease on the piston, too much eddy current losses, wrong number of windings, loose windings or an uncompatible feed force. If necessary, troubleshooting must be done to figure out what is causing the problem. When the machine is running smoothly in the test stand at 40V, the current, voltage, frequency and time is recorded.

8.2.3 Post driving test

The rigging of the post driving test was more complicated, as it entailed fabricating some custom clamps and arms, see Figure 8.6. A guiding tube was fixed with the clamps above a bucket of soil, the post and the post driver was then inserted into the guiding tube. After the rigging is complete, the container is closed and the post driver is controlled and monitored from the outside. A camera is streaming live from inside the container, so it can be monitored that everything is working correctly and when to stop the machine. When running the time, voltage, frequency and current is recorded. This data is later used to estimate the penetration rate. A mark is made on the post before and after every test, to be able to measure the penetration distance for the different tests.

Figure 8.6: Rigging of the post driving test, with custom clamps.

8.3 Test Results

Since rigging the measuring equipment were slightly complicated with the test stands needed. The tests were run without any of the measuring equipment from Resonator, due to lack of time and resources from Resonator personnel. For the electrical test, the current, voltage, frequency and time were measured. In the post driving test the same parameters were measured, and in addition the penetration distance.

8.3.1 Electrical test results

By watching the current while running the machine the resonance frequency was found at 21 Hz. When running this frequency the machine could be run up to 40V without exceeding the current limit, see Figure 8.7.

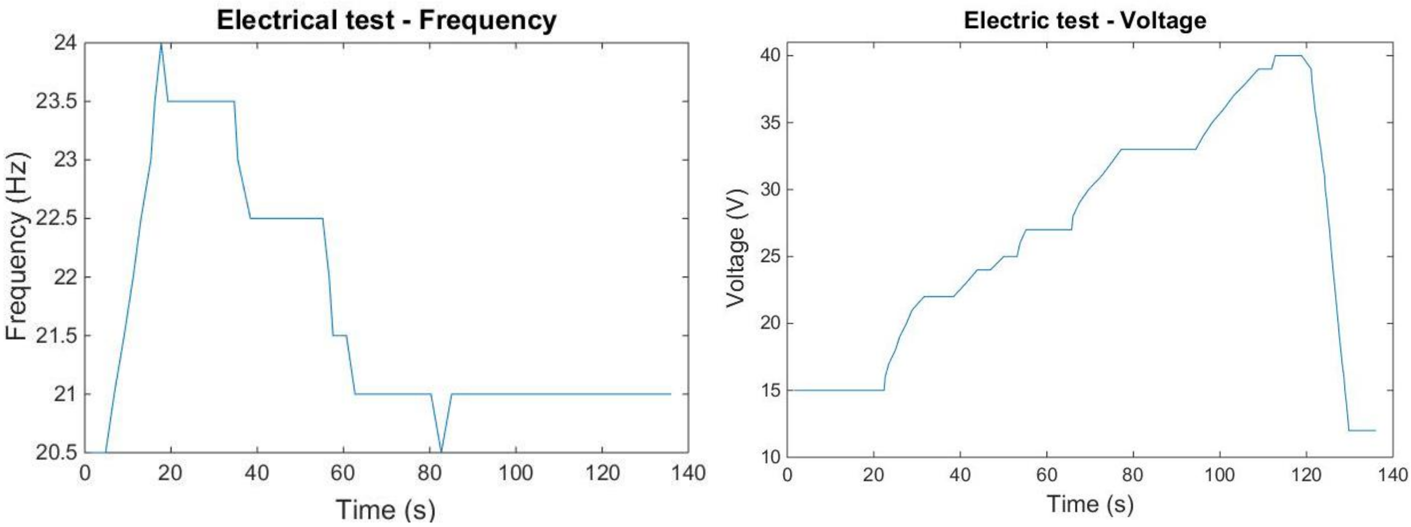


Figure 8.7: Figure 8.7a) on the left shows the electrical frequency of the machine when run during the electrical test. Figure 8.7b) on the right shows the voltage level during the test.

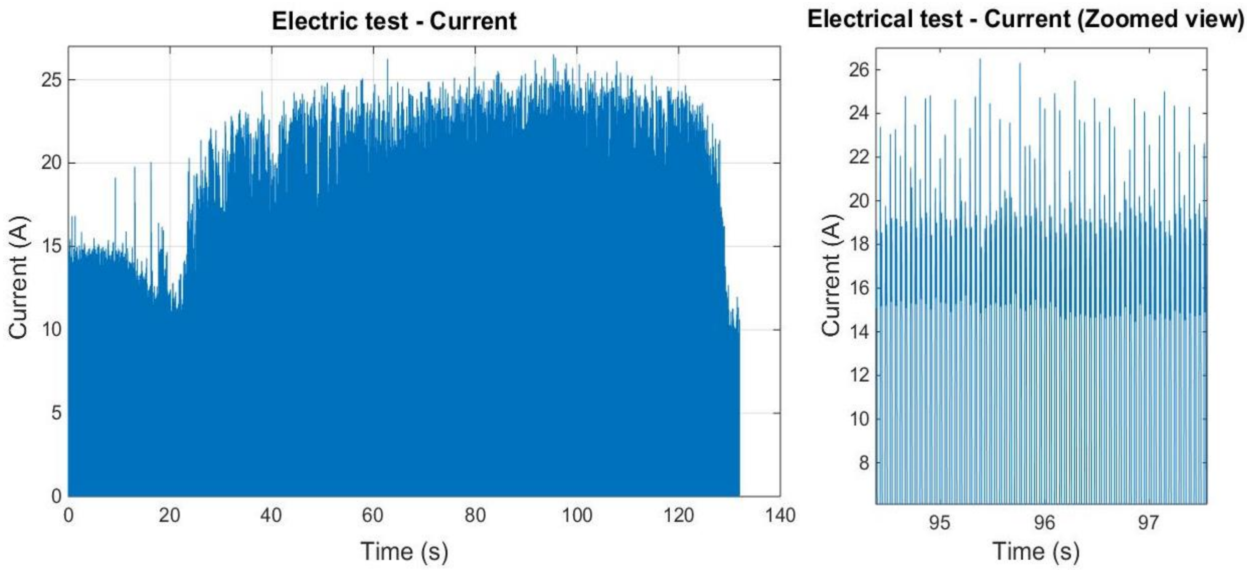


Figure 8.8: Figure 8.8a) on the left shows the electrical current of the machine during the electrical test. Figure 8.8b) on the right shows a zoomed view of the highest apparent value of Figure 8.8a).

Figure 8.8 shows the current level during the testing. The current level is measured over a long period of time, and is varying with a frequency of 21Hz, it is therefore difficult to interpret the illustration, where it seems like the current is much higher than 20A. The zoomed view in Figure 8.8b) shows that the RMS current is actually much lower than 20A, but some power spikes go above. These are not harmful, as it is the RMS current that is limited at 20A.

Since the machine was able to run at design values of 48V (40V + losses), and below 20A the electrical test is considered a success, and the post driving test can be run.

8.3.2 Post driving test

The post driving test was started off running with 21Hz and 40V. First runs was ineffective, as the test assembly started moving sideways from vibrations, instead of the post being driven into the soil. This was solved by placing heavy objects around the assembly, locking it in place. It worked to a degree, as it took longer for the assembly to move. Soil penetration was then successful at 21Hz and 40V, however the penetration rate was very slow and it took about 30 seconds to drive the posts 20mm. The frequency was then varied to attempt to find the resonance frequency when striking the post. Between 27 and 28Hz the penetration rate was found to be much better, however when increasing the frequency further the speed started declining. Issues with the wires being scratched and short circuited also cut the test short. However the results shown in Figure 8.9 and Figure 8.10 are quite promising. The RMS current in both tests is around 15A, this means that the machine can be pushed harder if necessary.

Rate of penetration:

- 27 Hz test gave a penetration of 65mm per 16s, this gives penetration rate of 24,4cm/min.
- 27,5 Hz test gave a penetration of 90mm per 13s, this gives penetration rate of 41,5cm/min.

The time values used to calculate the rate of penetration are extracted from Figure 8.9 and Figure 8.10. However, since the penetration stopped completely when the assembly started moving sideways and the post driver got stuck in the guidance tube, the time measurements are not accurate. This means that the real penetration rate is much higher than calculated above. The time values can be halved to give more accurate penetration rates.

Corrected rate of penetration:

- 27 Hz test gave a penetration of 65mm per 8s, this gives penetration rate of 48,8cm/min.
- 27,5 Hz test gave a penetration of 90mm per 6.5s, this gives penetration rate of 83cm/min.

Inputs to design learned from the prototyping test are:

- Current wires going from the windings must be well protected, and if running between the two end caps with the top spring, some slack on the wires must be allowed, to account for the movement of the machine relative to the top end cap, and avoid any scratches on the wires.
- A frequency dial is necessary to be able to fine tune the resonance frequency to different soil compositions.
- A low point of gravity is necessary to avoid the machine tilting and driving the post at an angle.
- It is necessary with a current limiting device, as the wires can overload if they are exposed to high currents. These can appear if the relative speed between piston and stator is below

design speed, this could happen if too much force is applied on top of the post driver or something similar.

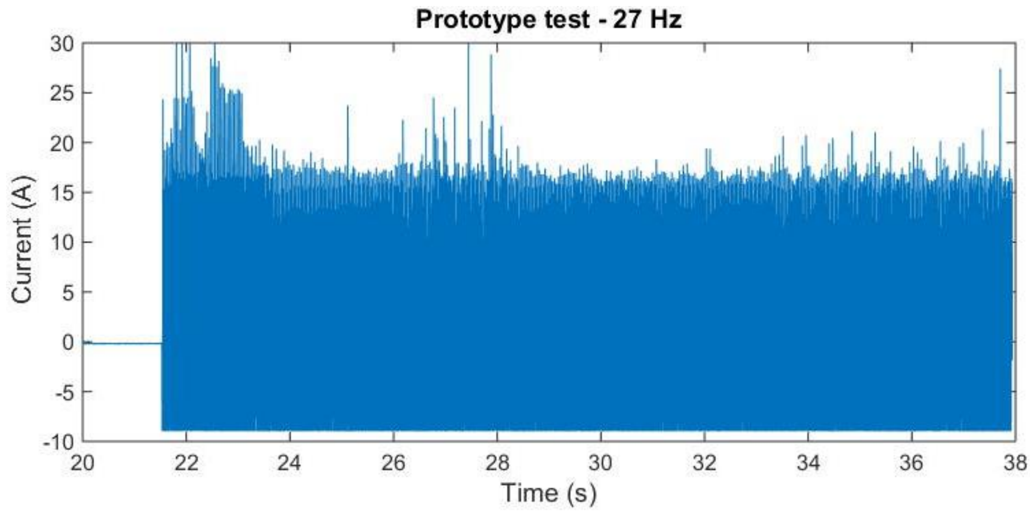


Figure 8.9: A plot of the current from the post driving test, running the machine at 27 Hz.

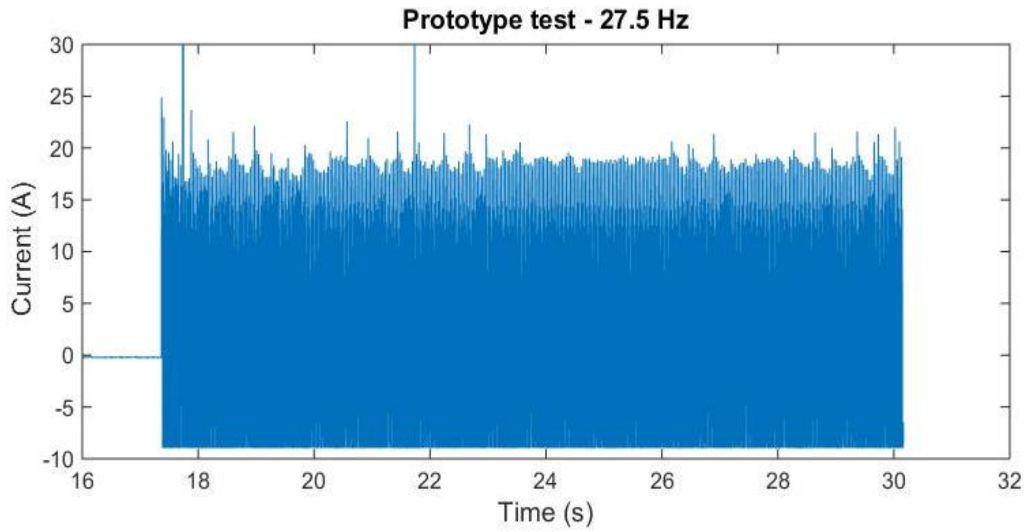


Figure 8.10: A plot of the current from the post driving test, running the machine at 27,5 Hz.

9 Product Architecture and Design

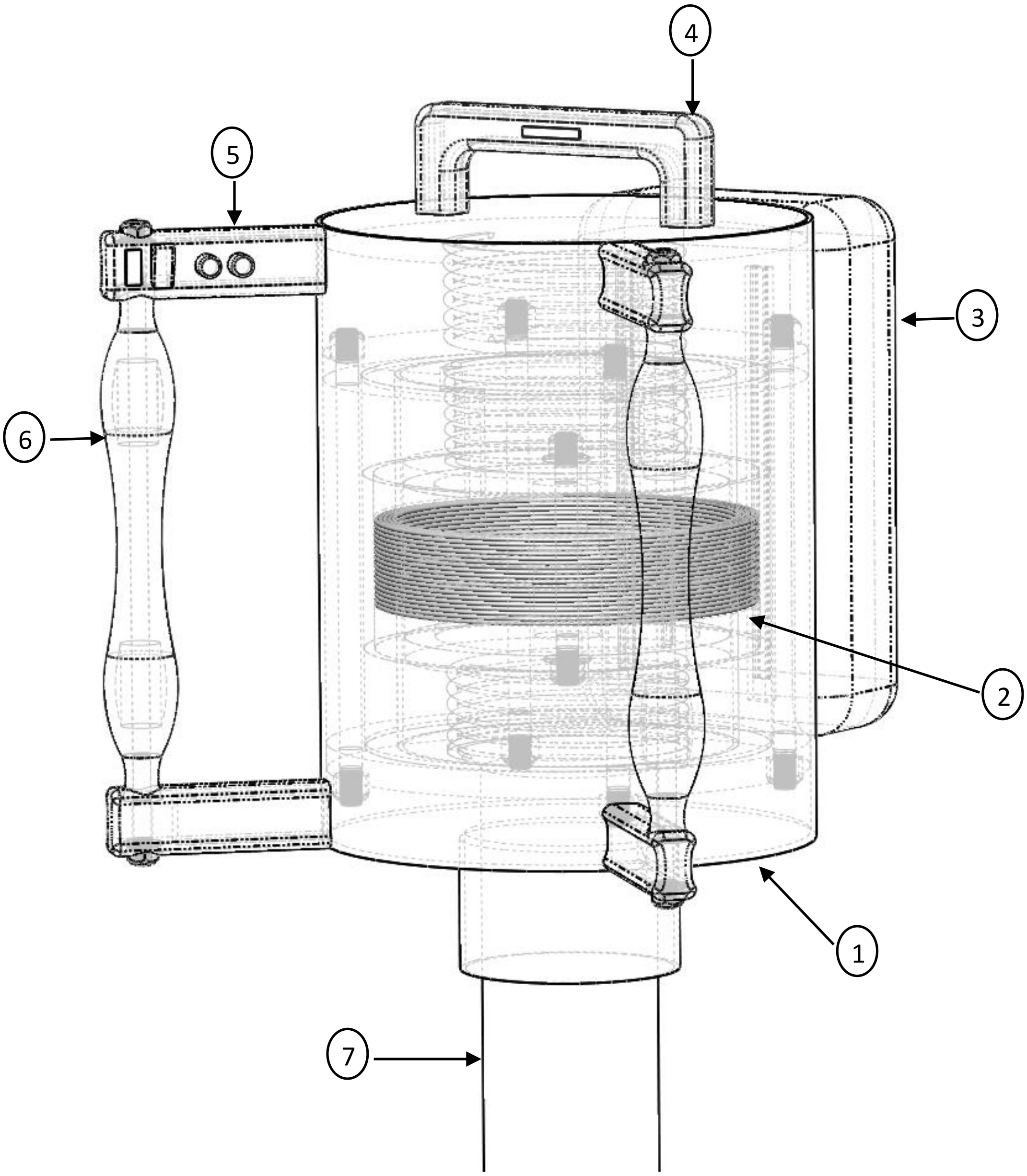


Figure 9.1: Assembly drawing of the E-Driver standing on a post. 1) E-Driver, 2) Internal electric motor consisting of a piston, a stator and springs, 3) power source, top handle, 5) control unit, 6) guiding handles, 7) wooden post.

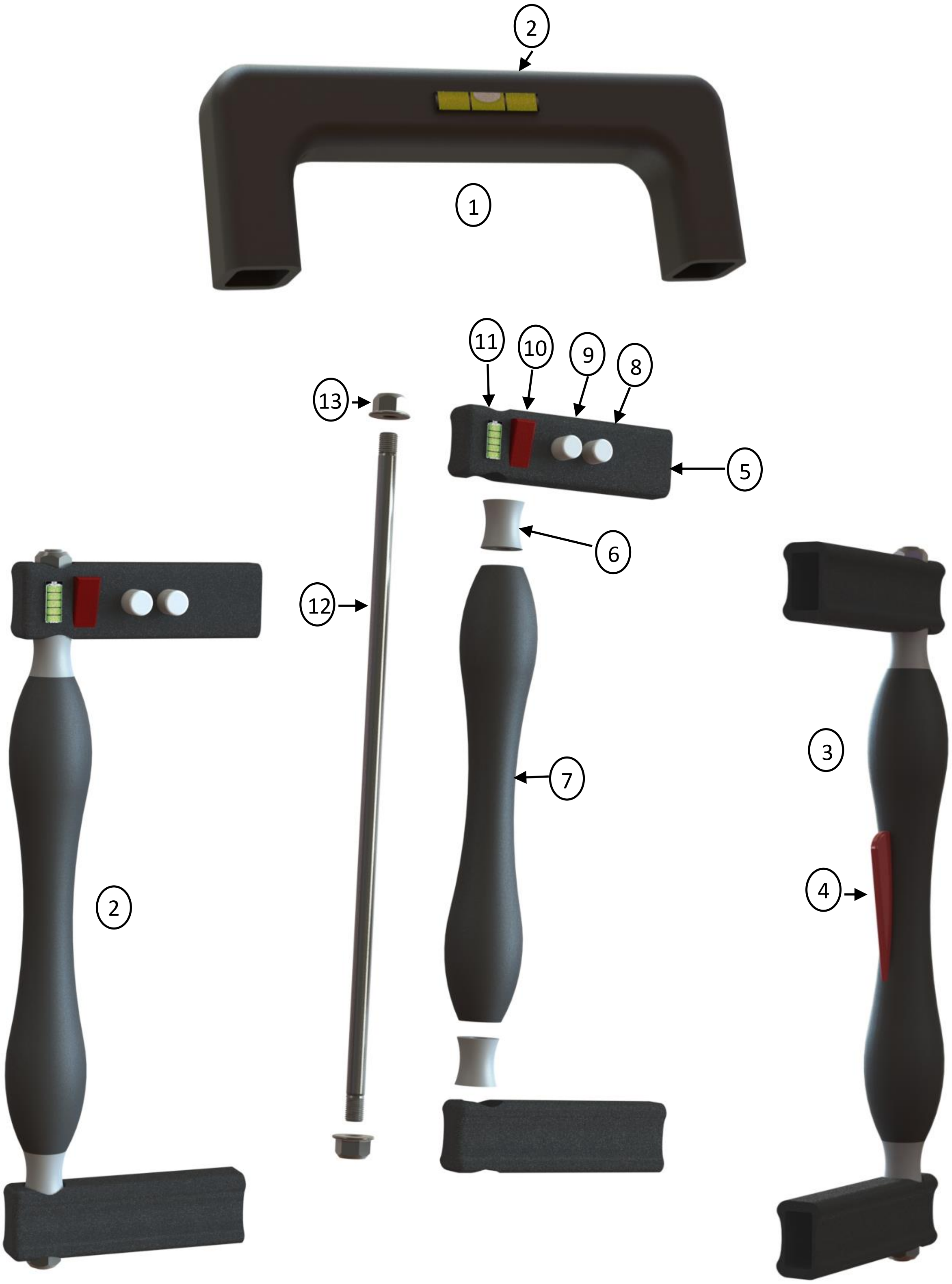


Figure 9.2: Renderings of the handles for the E-Driver. 1) Top handle hollowed out and with a carpenter´s level, 2) left handle, 3) right handle, 4) emergency stop, 5) Support arms for handles hollowed out for cable routing, 6) Dampers, 7) Handle grip, 8) Frequency tuning, 9) Power tuning, 10) on/off button, 11) Battery capacity indicator, 12) Handle bolt, 13) Locking nuts.

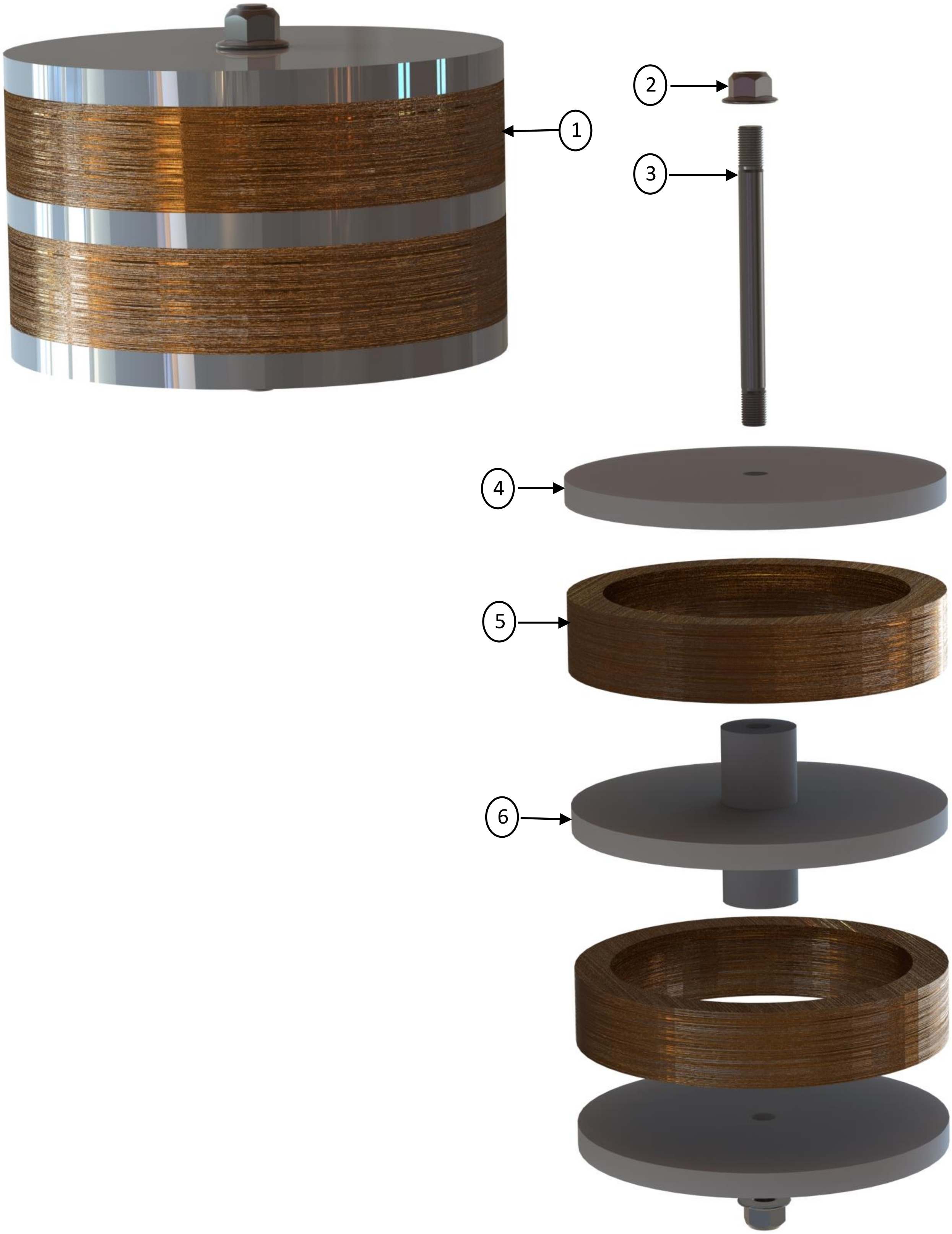


Figure 9.3: Renderings of the piston. 1) Piston, 2) locking nuts, 3) piston bolt, 4) end spacers, 5) permanent magnets in Neodymium N35 (HKCM Engineering e.K, 2015), 6) mid spacer with an extra extrusion on both sides to hinder that the magnets gets compressed too much.

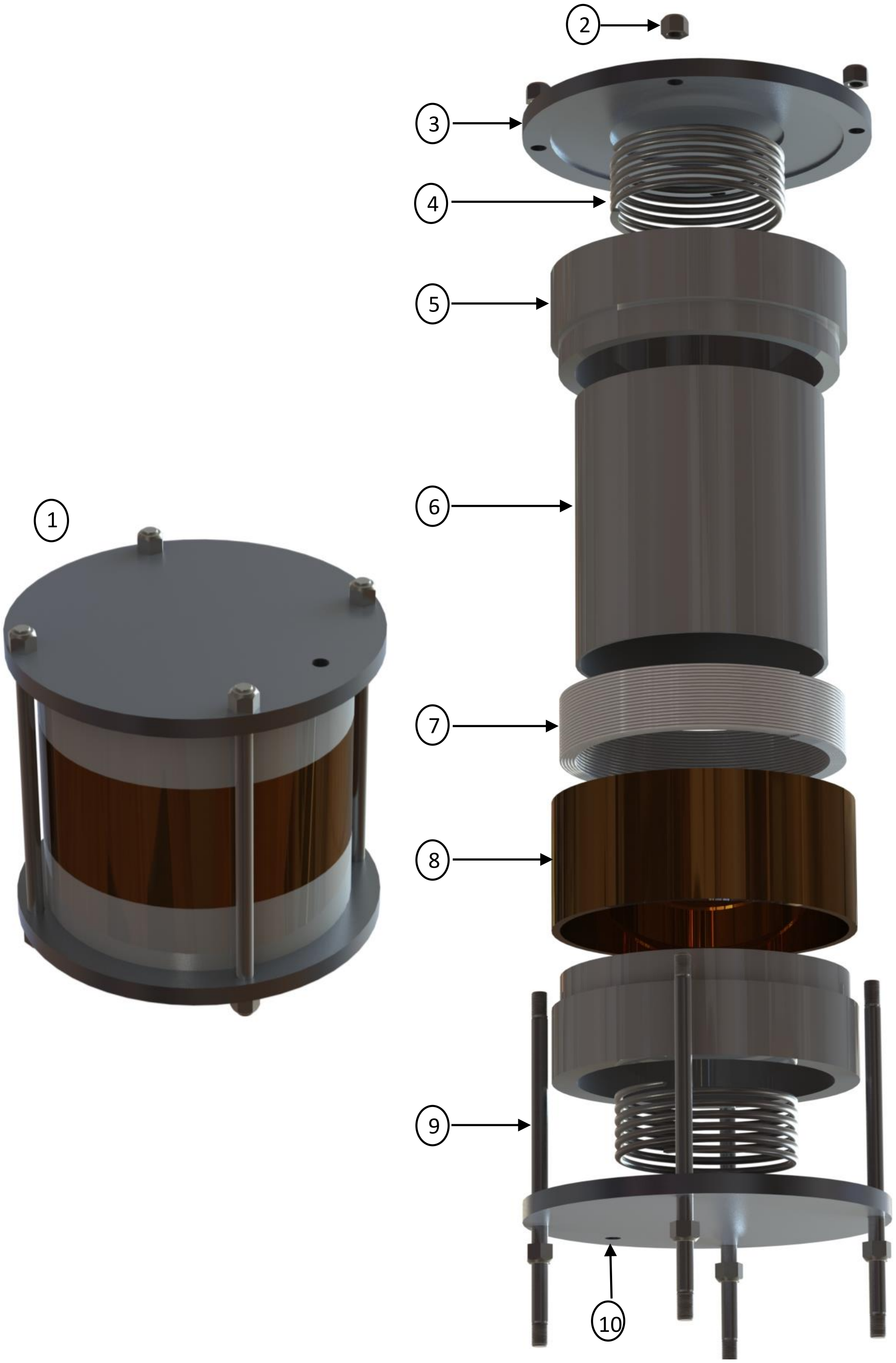


Figure 9.4: Rendering of the stator. 1) The stator, 2) Locking nuts, 3) Top/bottom end cap with boltholes and indentations for spring and top/bottom spacer, 4) springs, 5) top/bottom spacer, 6) piston tube, 7) winding, 8) SMC ring (insulated iron, 9) stator bolts, 10) hole for wires between the winding and the control unit.

Figure 9.5: 1) Picture of the real frog battery with approximate dimensions. Source: www.hallobattery.com.

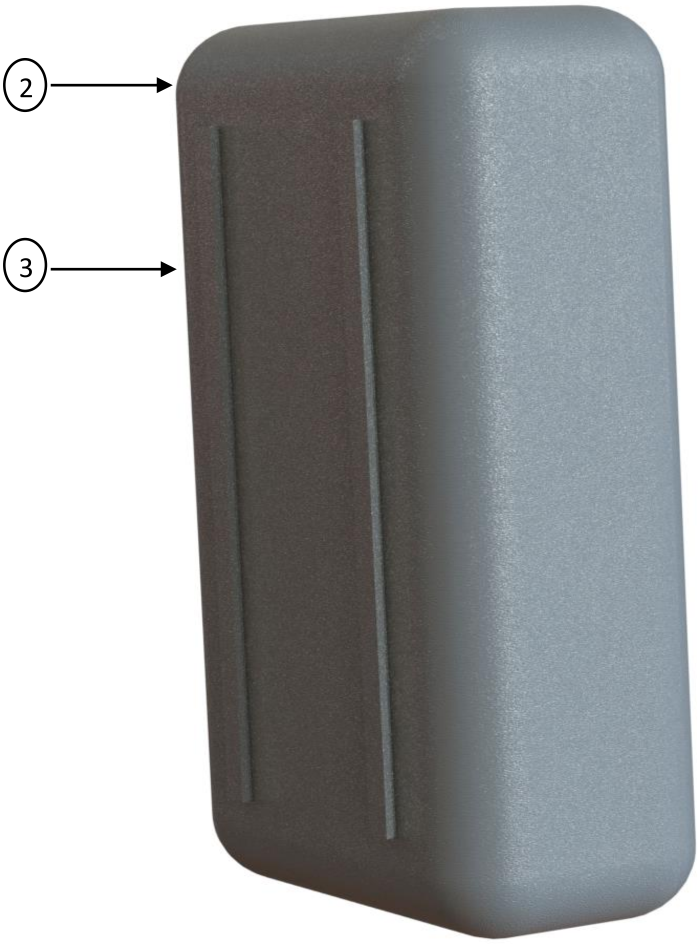


Figure 9.6: A rendering of the 3D CAD drawing of the battery with the same approximate dimensions. 2) Battery 3) mounting rails.

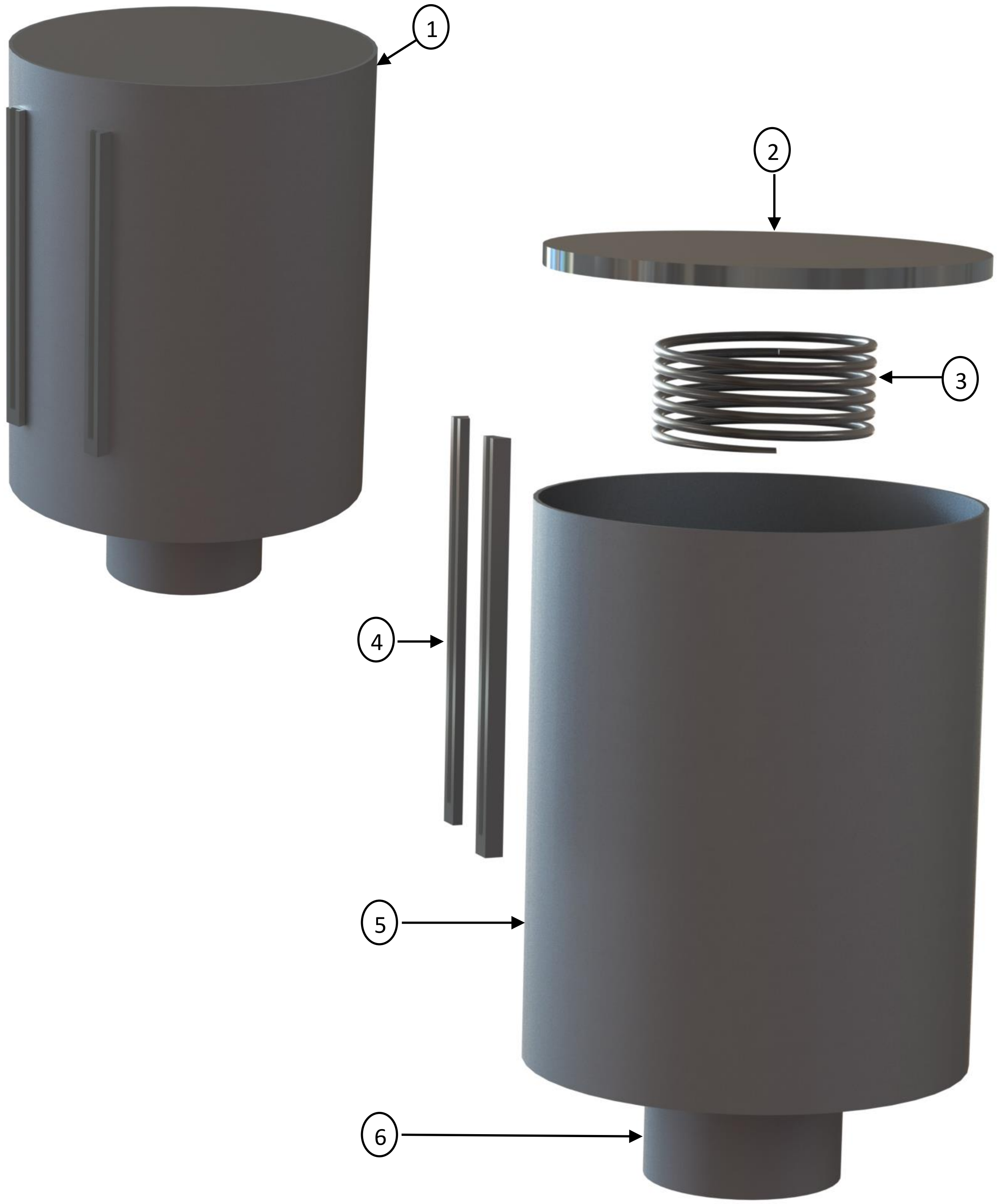


Figure 9.7: Rendering of the outer casing. 1) Outer casing, 2) upper endcap with threads (not visible), 3) top spring, 4) mounting rails for the power source, 5) outer casing sylinder, entry guide for the post. As the piston never goes past the spring, there is room for the electrical control unit at the top end cap, around the top spring. This also makes it easier with the cable routing to the battery, as there is no movement between the outer casing and the battery. This means that the flexible cable connection must be between the electrical control unit and the windings in the stator.

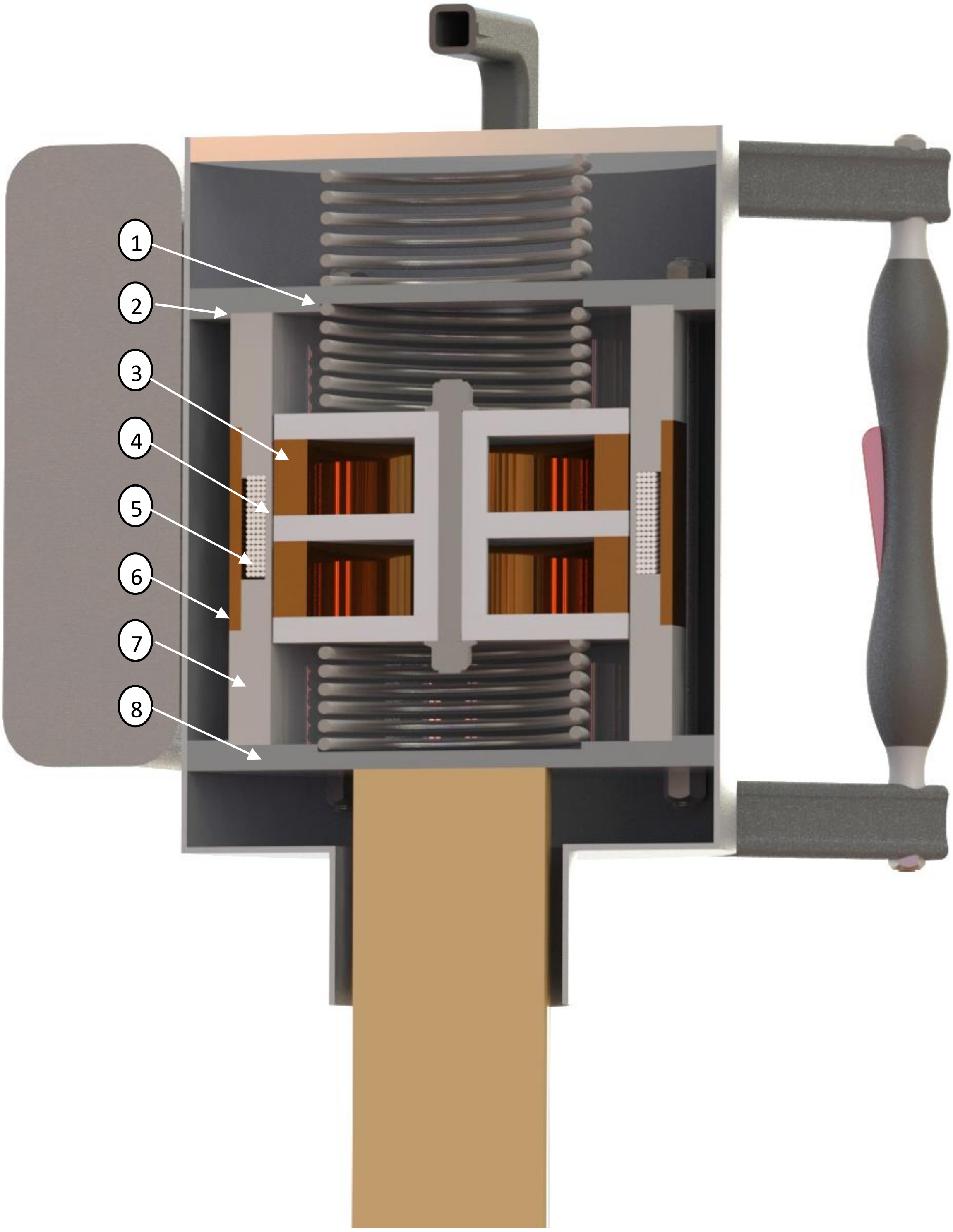


Figure 9.8: A section view of the E-Driver, illustrating how the internals are put together. 1) Indentation for internal spring, 2) indentation for top spacer, 3) permanent magnets, 4) piston tube (looks as if same component as the top/bottom spacers, 5) 4 layers of windings, 6) SMC ring, 7) bottom spacer, 8) bottom end cap.

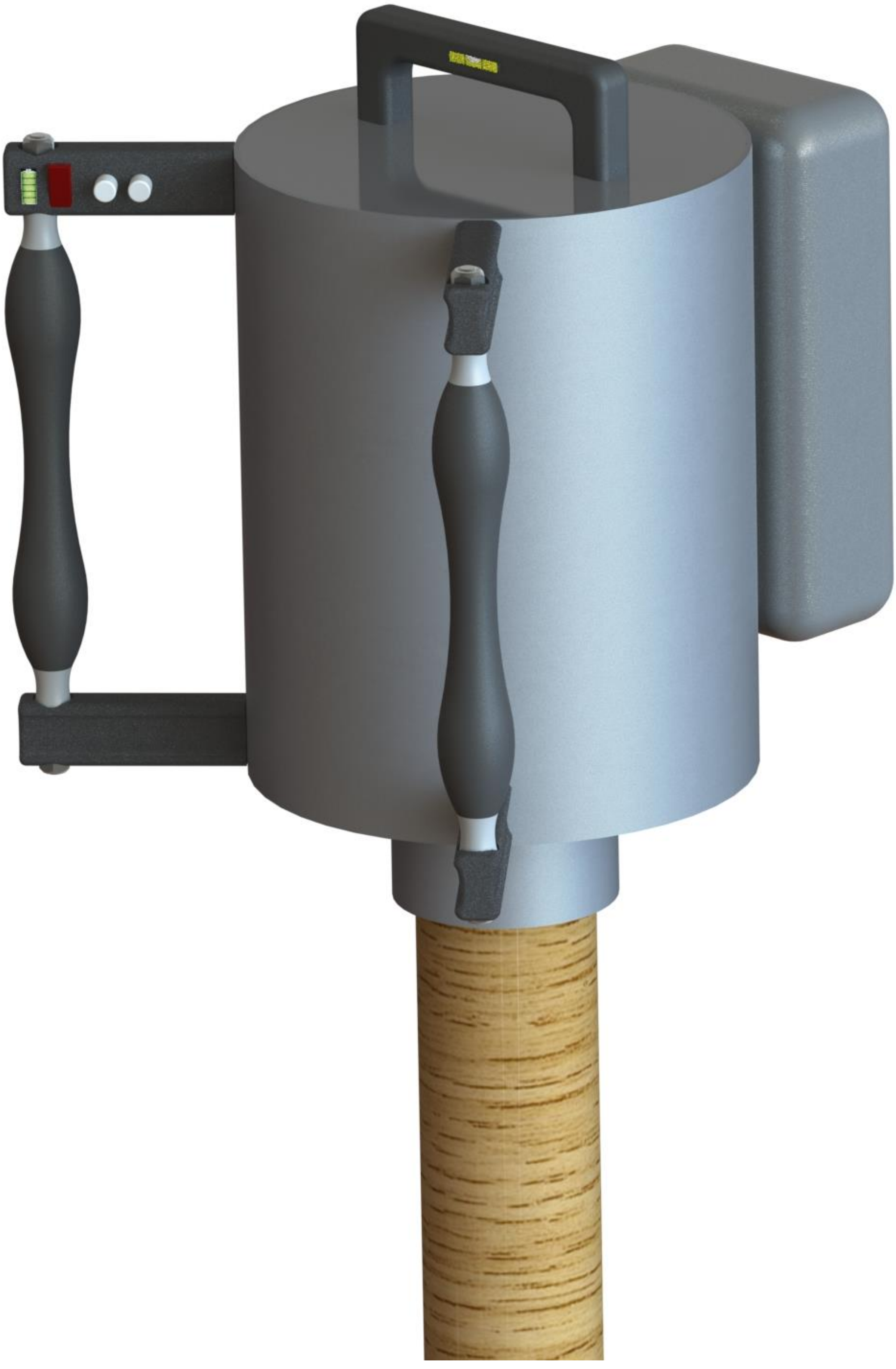


Figure 9.9: Rendering of the complete E-Driver, with all components and standing on a post. The total weight of the product, calculated from the 3D CAD is 16.5 kg.

10 Production and Economy

This chapter details the recommended production and assembly methods of the E-Driver split into its main components, and the production costs for both prototyping and mass producing the product.

10.1 Production Methods

In Table 10.1 all the components, the production method and the assembly of every main part is detailed. The exception is the electrical control unit, which has not been decided, however it can be bought ready made for a small cost. Most products can be fabricated in many different ways, the following methods are only recommendations. However the machine must be assembled in the same way as detailed, to ensure that the machine will function in the way it is intended.

Table 10.1: Recommended production methods for the individual components of the E-Driver, with figures from chapter 9 Product Architecture and Design.

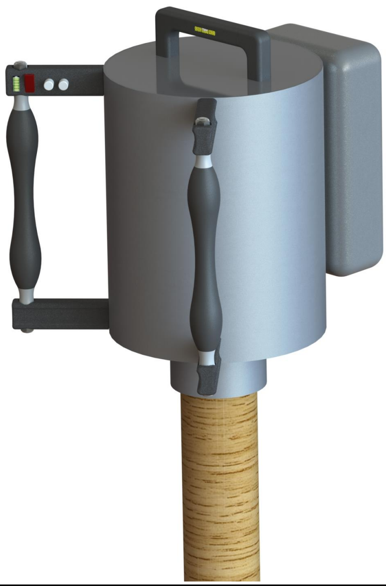
Piston 	**The piston consists of the following components:** 2 x M10 locking nuts – Purchased 1 x M10 bolt threaded on both sides – Purchased 2 x POM plastic end spacers, machined from a POM bolt, and a M10 hole drilled in the center. 1 x POM plastic mid spacer, machined from a POM bolt, and a M10 hole drilled in the center. 2 x permanent magnets - Purchased **Assembly of the piston:** The piston is assembled by first fastening one nut on the bolt. Then threading the pieces on in the right order. Care must be taken when placing the magnets, as they are very strong and can damage fingers or other components. The last step is to tighten the final nut. Make sure to smear grease on the piston before inserting it into the stator.

Table 10.1 continues: Recommended production methods for the individual components of the E-Driver, with figures from chapter 9 Product Architecture and Design.

<table>
<tr>
<td>Stator
</td>
<td>The stator consists of the following components:
8 x M8 locking nuts – Purchased
4 x M8 bolts, threaded on both sides – Purchased
2 x End caps in 6063-T6 aluminum cut from an aluminum bolt, with 4 x M8 bolt holes drilled at the centerlines, with indentations machined to fit the spring and the end spacers. The top end cap is also fitted with a 10mm hole for penetration of cables to and from the winding.
1 x POM plastic piston tube with 2mm thickness cut and machined from a POM tube.
2 x POM plastic end spacer, cut and machined from a POM tube to correct dimensions. One end spacer has an additional groove machined for cable entry and exit.
1 x 2mm windings in 4 layers.
1 x SMC ring – Purchased
2 x Springs – Purchased

Assembly of the piston:
Assembly must take place after the piston is assembled, as the piston must fit inside the stator. First step is to make the windings from a 2mm copper wire, on the piston tube. The spacers must first be placed on the tube to make the windings on the correct spot, then it must be locked in a rig where it can turn, for example in a turnery. The windings are then tightly wound around the piston tube in 4 layers. Some extra wire must be kept at both start and finish. Now the top end cap can be removed, and the SMC ring can be threaded onto the piston tube, outside the winding. Make sure the extra wires goes into the groove of the top end spacer before replacing it. The next step is to screw 4 locking nuts onto one end of each bolt, then all the components can be placed in the following order:
Top end cap.
Top spring.
Piston tube with end spacers, winding and SMC ring, make sure the extra wires is inserted into the M8 hole in the top end cap.
Insert piston into the piston tube.
Insert the bottom spring.
Thread the bottom end cap onto the bolts.
Fasten with 4 locking nuts on the bolts, the springs are both 10mm too long in normal state and must be pre-compressed.
Align the end spacers to fit into the groove of the end caps when tightening.</td>
</tr>
</table>

Table 10.1 continues: Recommended production methods for the individual components of the E-Driver, with figures from chapter 9 Product Architecture and Design.

Outer casing 	**The outer casing consists of the following components:** 1 x Aluminum tube machined to correct dimensions, with threads on the upper part. 2 x Fastening rails for the battery in extruded aluminium, either bolted or welded to the outer casing. 2 x Endcaps, the upper endcap to be threaded to fit the tube, the lower endcap to be drilled a hole in the center and welded to the bottom of the tube. 1 x Aluminum tube, welded to the bottom endcap, with hole dimensions equal to the drilled hole in the bottom endcap.
Handles 	**The handles consist of the following components:** 4 x Support arms for handles, in extruded aluminium. One arm is also outfitted with the following electrical components: - 2 x Turnable buttons - 1 x on/off button - 1 x Battery indicator 4 x Dampers – Purchased 2 x Handholds – Purchased, one with emergency stop. 2 x Bolts through handholds – Puchased. 4 x Locking nuts for the bolts – Purchased. 1 x Top handhold, made from bent extruded aluminum. 1 x Carpenter´s level riveted to the handhold – Purchased.
Assembly 	**Assembly of main components:** 1. The vertical handholds are welded to the outer casing. 2. The top handhold is bolted/welded to the top endcap. 3. The top spring is fastened to the underside of the top endcap, and to the top of the stator. Preferred method is to use bolts and clamps on the underside of the spring, as welding on the spring will damage the material.

10.2 Production Cost

Production cost vary vastly from prototype production to mass production. This is because of one time costs, increased efficiency when producing many and in the production of the components a lot of time goes to rigging and maybe programming the machines. This is done only once when mass producing, which cuts down on the man-hours necessary to complete the work. Also when purchasing materials it is common to only be able to buy a standard length, for example 1 meter bolts of aluminum etc, meaning it might be necessary to buy too much material. Also prices are lower when buying in large quantity.

For the production costs, prices for magnets, smc rings and springs are estimated from similar products purchased by Resonator. Production and materials are based on estimated prices from senior engineer Bjørn Brenna at the NMBU workshop. The battery price is estimated from different internet prices, the other electrical components are mostly guess-work, but they consist of a very small part of the total cost.

10.3 Cost for Prototype Production

Table 10.2: Estimated cost for developing and prototyping the E-Driver, with detailed type of work for concept development and production cost, and materials and components.

CONCEPT DEVELOPMENT	Hours	Amount	Price, NOK	Sum, NOK
Research and theory	130		550	71 500
Concept testing	20		550	11 000
Concept development and design	120		550	66 000
3D CAD	160		550	88 000
Project report	100		550	55 000
Construction drawings	20		550	11 000
Part sum, concept development	**550**		**550**	**302 500**
PROTOTYPING				
Production				
Cutting / drilling work	3	1000		3 000
Welding work	7	1000		7 000
Turnery work	17	1200		20 400
Winding work	1	1000		1000
Assembly work	2	1000		2000
Materials and components				
Plastic POM tube (for piston tube and spacers) (28,4kg/m)		1m	100/kg	2 840
SMC tube		1m	300/kg	2 000
Aluminum 6063-T4 tube (150kr/kg) (for outer casing)		1m	150/kg	2 000
Aluminum 6063-T4 tube (for sleeve for post)		1m	150/kg	400
Aluminum 6063-T6 bolt (for endcaps)		1m	150/kg	12 750
Magnets		2	200kr	400

Table 10.2 continues: Estimated cost for developing and prototyping the E-Driver, with detailed type of work for concept development and production cost, and materials and components.

2mm copper wire (for the winding)		25m	150/35m	150
Bolts & locking nuts in SS316 (for stator, handles, piston)		3m	150/kg	180
Aluminum 6063-T4 top handle		3	150/kg	15
48V Frog battery		1	3500	3 500
Aluminum 6063-T4 rails (for battery fastening)		2	150/kg	30
Dampers (for handles)		4	100	400
Springs		3	300	900
Carpenter´s level		1	100	100
Turnable buttons		2	80	160
On/off button		1	50	50
Battery indicator		1	300	300
Control unit		1	200	200
Cables (for electrical components)		3m	150/35m	150
Handhold w/ emergency stop		1	500	500
Handhold		1	300	300
Extrusion tool for aluminum extrusions		2	20 000	40 000
Part sum, prototyping		**1 unit**		**75 325**
Total cost for developing and prototyping the E-Driver			**377 825 NOK**	

10.4 Cost for Mass Production

Table 10.3: Estimated cost for developing and mass producing 500 units of the E-Driver.

CONCEPT DEVELOPMENT	Hours	Amount	Price, NOK	Sum, NOK
Research and theory	130		550	71 500
Concept testing	20		550	11 000
Concept development and design	120		550	66 000
3D CAD	160		550	88 000
Project report	100		550	55 000
Construction drawings	20		550	11 000
Part sum, concept development	**550**		**550**	**302 500**
MASS PRODUCTION				
One time cost				
Extruding tool for aluminum extrusions		2	20 000	40 000
Welding robot		-	-	250 000
Welding gir		-	-	250 000
Welding jig´s		-	-	100 000
Part sum, one time cost				**640 000**
Production cost				
Cutting / drilling work	0.3	1000		300

Table 10.3 continues: Estimated cost for developing and mass producing 500 units of the E-Driver.

Welding work	0.7	1000		700
Winding work	0.1	1000		100
Turnery work	1.7	1200		2 040
Assembly work	0.2	1000		200
Part sum, production cost		**1 unit**		**3 340**
Material- and component cost				
Plastic POM tube 60kr/kg (for piston tube and spacers)		0.25m		40
SMC tube		1		60
Aluminum 6063-T4 tube (for outer casing)		1	60/kg	120
Aluminum 6063-T4 tube (for sleeve for post)		1	60/kg	40
Aluminum 6063-T6 bolt (for endcaps)		0.03	60/kg	180
Magnets		2	50	100
2mm copper wire (for the winding)		25m	50/35m	30
Bolts & locking nuts in SS316 (for stator, handles, piston)		3m	60/kg	20
Aluminum top handle		1		15
48V Frog battery		1		2 000
Aluminum rails (for battery fastening)		2		30
Dampers (for handles)		4	60	240
Springs		3	150	450
Carpenter´s level		1	50	50
Turnable buttons		2	30	60
On/off button		1	20	20
Battery indicator		1	150	150
Control unit		1	100	100
Cables (for electrical components)		3m	50/35m	5
Handhold w/ emergency stop		1	200	200
Handhold		5m	100	100
Part sum, material- and component cost		**1 unit**		**4 010**
Part sum, unit cost			7 150 NOK	
Total cost for mass producing 500 units of the E-Driver			**4 517 500 NOK**	

As not only the production cost of the product is included in the final cost, there is also packing, shipping, and the sales method. The sales method can either be by a vendor or by a web. An additional 1 500 NOK is added to the estimated price to account for these additional costs. The total estimated price for the E-Driver is then calculated by the following method:

$$Estimated\ price = \ unit\ cost * \frac{one\ time\ cost + concept\ development}{Amount\ of\ units} + 1500 \quad (10.1)$$

Equation (10.1) gives an estimated shelf price of **10 535 NOK** for the product, when mass producing 500 units. As the preferred price for the product is 10 000 NOK the amount of units necessary to be produced in order to achieve this price can also be calculated from Equation (10.1).

Amount of units to be produced in order to get a shelf price of 10 000 NOK is 698 units.

11 Market Presentation

Figure 10.1: 3D CAD rendering of the final design on a post in a field. Field source: http://feelgrafix.com/

Figure 11.2: Renderings of the final design of the E-Driver with different colors.

Figure 11.3: Enlarged rendering of the E-Driver with pale blue and black colors.

12 Process Evaluation and Discussion

12.1 The Development Process

The project plan set up in the beginning of the project was an ideal situation, and it was not possible to follow completely. The theory part was more time consuming than expected, this was mostly because of difficulty finding good sources. Some external situations also caused some delays, for example the workshop closed down and took a very extended easter holiday just when I was in the fabrication process. Also Resonator was busy with their own testing and test rigging just when I was ready to do my testing. This could have been avoided by better planning in co-operation with the required resources.

In the start of the project a lot of technical details needed to be understood before a design could be attempted. The theory behind the Resonator motor is complicated with several different technologies involved. To make it more difficult, not a lot of technical research or papers in the field of post drivers were available in books or on the web. On the subject of pile drivers in support for structures, a lot of research have been done. Some of this research was useful, however the pile drivers operate with a lot higher force and heavier weights, so most was not relevant for the post driver. This led to splitting up the technology required in the post driver into its components and researching every part individually.

In the development process it was a lot back and forth, especially with the motor design. As this was a process in co-operation with Resonator, who was busy with their own project, it was sometimes hard to get the required information. The motor design took quite a lot of time, as everyone had their own idea of what the product should look like and which motor should be used, before any evaluation or screening process had been done. This led to several attempts at trying to use different motors, but either getting enough force with the required weight or low enough cost proved to be troublesome. Because of this the only viable motor was a modified and enhanced version of the light P2 motor. Even though this used up a lot of time, the development process benefited greatly from this. A lot of external inputs were received, and a lot of different solutions were discarded, this made the end result better. The rest of the functions evaluated in the concept development had less impact on the design and required minor research to decide. For these functions more external inputs could have been helpful and given more alternatives, but the time schedule was getting a bit short at this point.

The prototype post driver was very simplified since the workshop had very few resources available, so the prototype was mostly limited to my knowledge of the machining tools in the workshop. Also a lack of materials made some parts impossible to fabricate without buying new materials. This led to a prototype design without an outer casing, which makes it impossible to fasten the outer casing to the post during the post driving test. As this is the case in the dynamic model, where the top spring cannot move upwards, the impact power reached in the dynamic model will most likely not be the same. If the machine is more or less efficient, when fastened to the post, should be further tested with the final design.

12.2 Testing

The drop test went very smoothly, with good test results. The average rate of penetration from 20 J was very promising. The only issue was the soil used, as this is not a true representation of the soil outside. A lot of different compositions and grades of compression can be found. The soil used in the test contains little organic material, and is estimated to be a soil type that is relatively easy to drive posts in. Ideally a soil type that is difficult to drive posts in should be used.

The electrical test also went smoothly. Only minor rigging of the test stand was necessary before the machine could be connected and run. The machine was then able to run at the required values for the voltage, current and frequency. The heat production of the machine could not be measured, as the equipment necessary was not readily available. However a spot check was done by hand, and the machine felt “cool” to the touch, so the heat is not assumed to be a problem. To be certain the temperature needs to be measured during an extended test time, with the final design.

The post driving test got a bit more problems. Just the rigging of the test stand took almost a full day to complete, this was because several custom made clamps needed to be fabricated. Then after the rigging was complete the first attempts at driving the post failed, as the bucket of soil started moving sideways from the vibrations instead of the post being driven into the soil. This led to fixing everything in place by placing heavy objects around the bucket of soil and the test stand. Some good runs were then completed, before the wires started to short circuit. The electric cables were placed underneath the stator bolts and vibrations caused the cable sheath to be damaged and the system then shortcircuited. After removing the post driver from the test stand the issue was corrected and two more tests were run, before the same issue appeared. For final design it was obvious that the cable routing needed to be done differently. The same issues with the soil as in the drop test is present in this test. Some decent test results were recorded, however the rate of penetration was much lower than in the drop test. This can be because of issues with the prototype design, the test rigging or that the dynamic model needs to be improved.

12.3 Design Revision

A product can almost always be improved, and usually undergoes frequent design revisions. The E-Driver also has items that can be further developed for the next design. It would be preferrable to fabricate the final design before any further design revisions are done. As the testing of this product out in the field in different soil composition most likely will give many valuable inputs. Some items that then should be further investigated are listed below.

- Frequency scale – The frequency scale is not yet developed, as this requires testing the post driver in different types of soil and estimating what frequency is optimal to achieve resonance.
- Method for fastening the outer casing to the post – This method should be tested to see if more or less efficient, and if more efficient to be included in next design.
- Tuning to improve the efficiency of the machine.
- Increasing the battery size – The running time of 30 minutes can be increased by having a bigger battery, this is very easy to incorporate in the design, however it should be tested how easy it is to handle the product with the current design.

12.4 Other Fields of Application

The post driver can be customized to drive most objects into the soil, unless they are too big and require too much force. For the post driver to be applicable for use in other fields of application, for example as a vibrator that can be clamped onto an inclined surface and move objects, make things loose, etc. so many changes to the design is required that it would be a completely new product.

13 Conclusion

In this project a novel handheld electric post driver has been developed. The E-Driver is much cheaper than other motorized competitors and it is just as light and easy to use. The E-Driver is powered by a battery source and driven by a linear electric motor. The development process and results has been detailed and presented in this master-report. The efficiency of the machine has not been verified in a proper environment and so cannot be concluded. In order to reach the desired shelf price of 10 000 NOK per unit an estimated number of at least 698 units must be produced to make a profit. In Table 13.1 the specifications that has been the result of the development process are summarized.

Table 13.1: Specifications for the E-Driver.

Attribute	Value
Weight	16.5 kg
Electrical frequency	27.5 Hz
Battery size and type	48 V Frog battery, 11.6 Ah
Height	392 mm with handle
Width	285 mm, 350 mm (with handles and battery)
Calculated impact power	20 J
Corrected rate of penetration	83cm/min
Production price per unit (prod. of 500 units)	7 150 NOK

13.1 Recommendations

Several traits makes the E-Driver an attractive product.

- Intuitive user interface.
- Lightweight product, easy to handle.
- Cheap compared to competitors.
- Driven by electricity, no hassle with oil or fuel.
- Everything necessary to use is in one unit.
- Battery can either be recharged or exchanged with a spare.
- Safe to use.
- Solid and durable design, not many fancy exposed parts.

13.2 Continuing Work

- More complete market research should be done, to find potential parties interested in selling and/or buying the product, as well as their inputs to the design of the E-Driver.
- The final design needs to be prototyped and tested in a real environment on a real post in order to get accurate results for the rate of penetration.
- It should be tested whether or not fastening the post driver to the post is more or less efficient.

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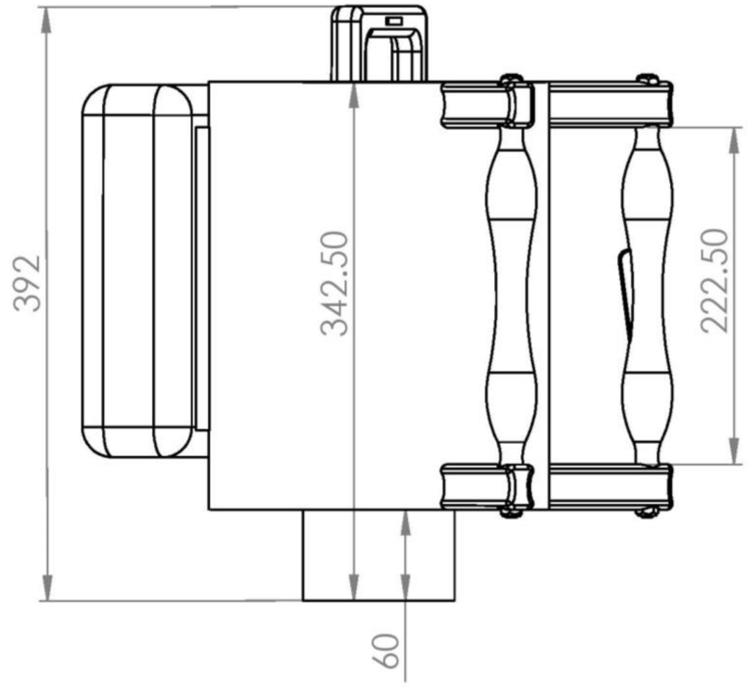
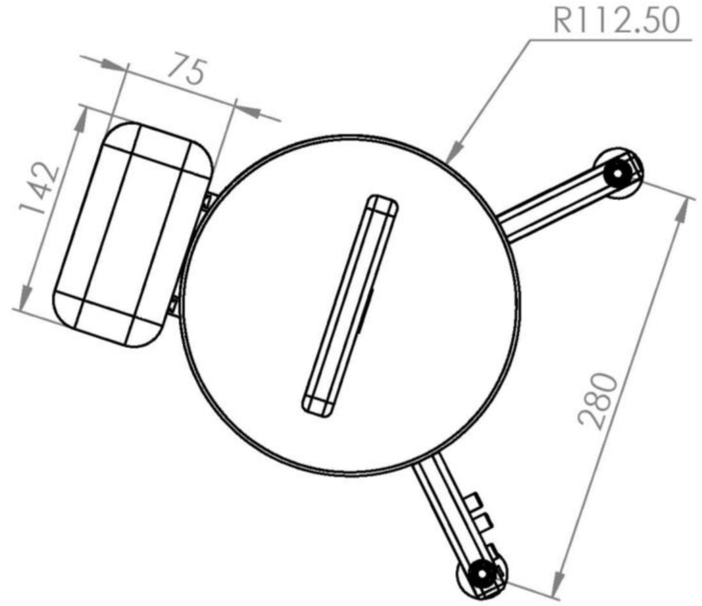
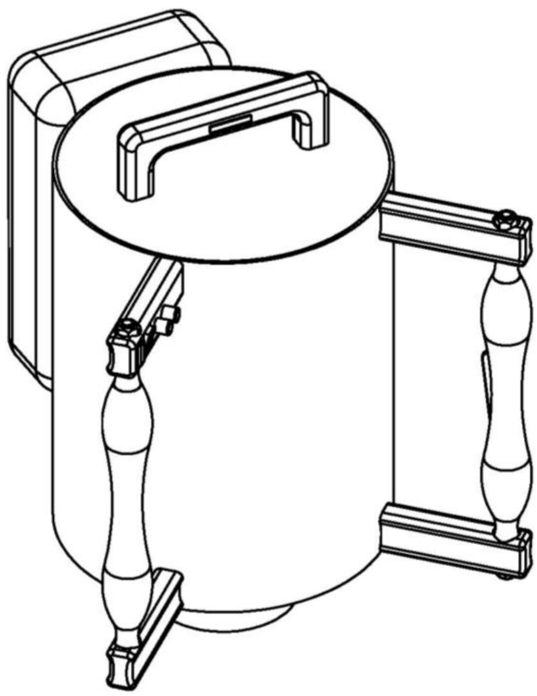
Pictures used in SolidWorks decals
Battery capacity - http://www.etel-group.com/
Carpenter´s level - https://lh6.ggpht.com/

15 Attachments

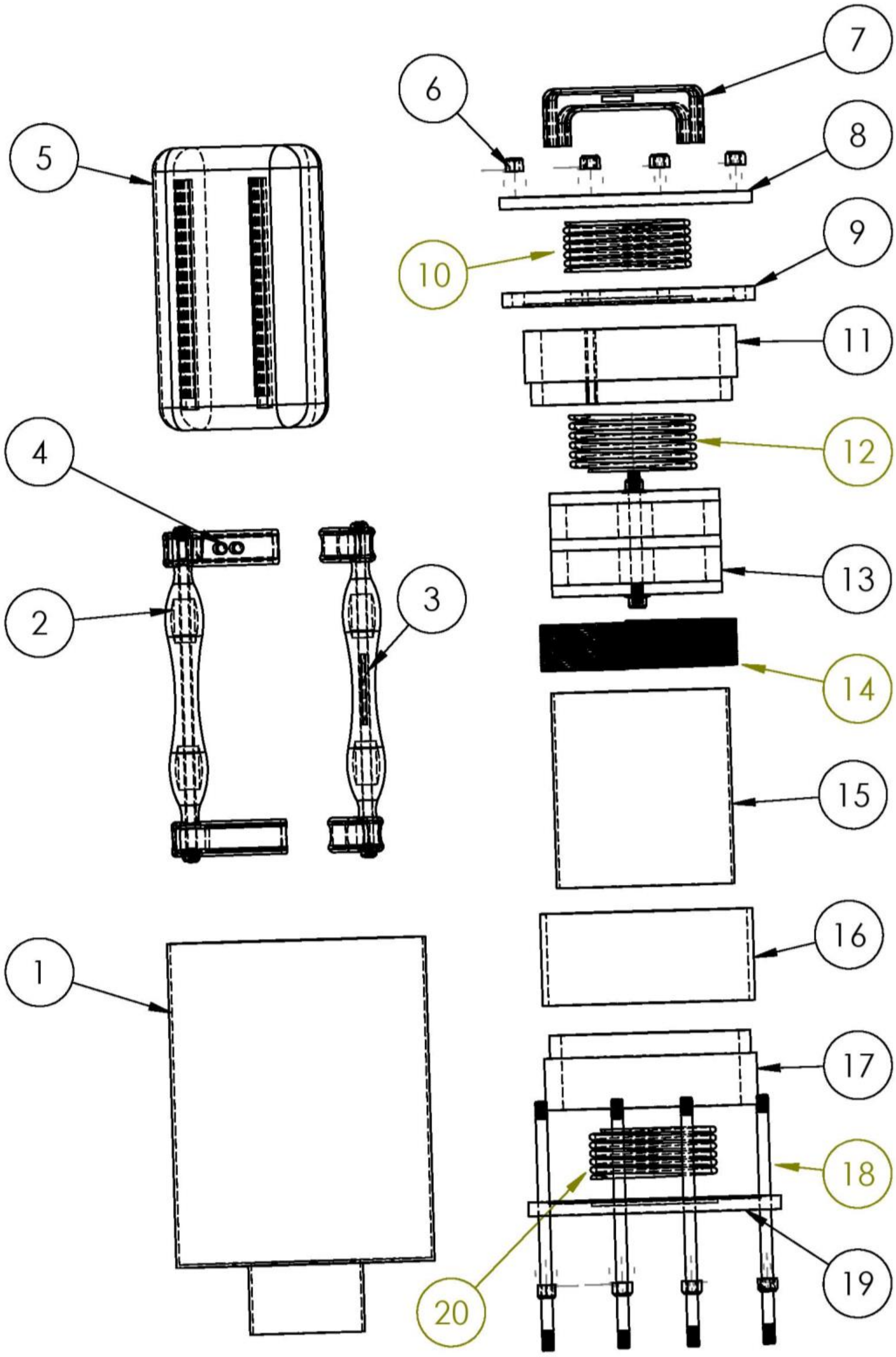
1. Assembly drawing Edr_as_001 with main dimensions.
2. Explosion drawing Edr_exp_001 with numbered main components.







WEIGHT: 16.5kg	REVISION: 1
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS	
TITLE: E-Driver, main dimensions	
DWG NO. Edr_as_01	A4
SCALE:1:10	SHEET 1 OF 1



Item NO.	Component	Details	Item NO.	Component	Details
1	Outer casing	With welded on sleeve	15	Piston tube	Plastic POM tube
2	Vertical handle	Handle with dampers	16	SMC ring	Magnetic isolator
3	Emergency stop	Button on the handle grip	17	Bottom spacer	Magnet spacer
4	Handle arm	With control buttons	18	Bolts	Stator bolts
5	Battery	Frog battery 48V w/rails	19	Bottom endcap	Endcap in SS316
6	Locking nuts	8 Locking nuts for stator	20	Bottom internal spring	Loose spring, pre-compressed
7	Top handle	With carpenter´s level			
8	Upper endcap	Aluminum endcap w/threads			
9	Top endcap	Aluminum endcap			
10	Top spring	Fastened at both ends			
11	Top spacer	Includes groove for cables			
12	Top internal spring	Loose spring, pre-compressed			
13	Piston	With bolt, spacers and magnets			
14	Winding	2mm wire wound on piston tube			

TITLE:

E-Driver, Explosion drawing

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