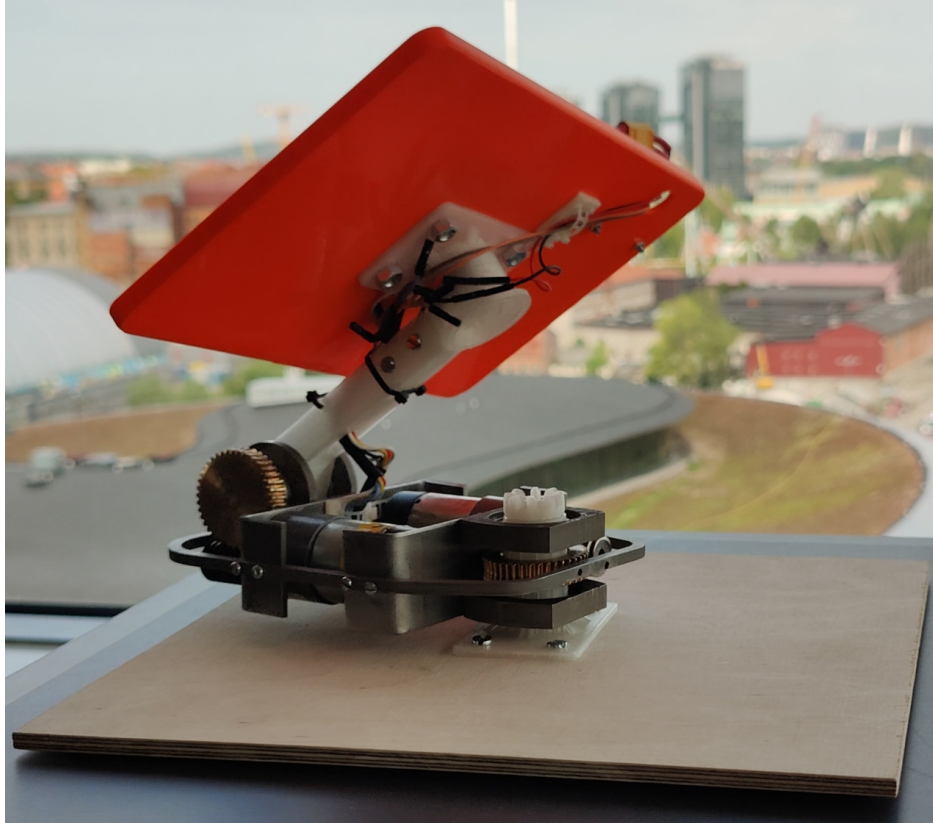




CHALMERS
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Design of an Auto-pointing System for a Geostationary Earth Orbit Application

Master's thesis in Product Development

ERIC JARNESTÅL
STAFFAN STAF

Industrial and Materials Science

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
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MASTER'S THESIS 2023

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Cover: An image of the finalised Auto-Pointer prototype, pointing toward a hypothetical satellite above the Gothenburg skyline.

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Abstract

This report documents a masters thesis in which a systematic product development process was applied to create an auto-pointing subsystem for a satellite internet user terminal. The current product of Satcube AB is a manually operated terminal, hence the need for an automated alternative. The aim of the project was to explore the undiscovered solution space of minimally actuated, automated antenna pointers. The sub-system should only utilise two actuators for the antenna's three axes of rotation requiring a state-of-the art design. Furthermore, to be inline with Satcubes product portfolio and the market trend, the product should be compact and light weight to ensure high portability.

From conceptualisation to detailed design, an agile prototyping approach was implemented with additions of rapid prototyping, mainly with 3D-printers, which proved to be important. The design process progressed in iterative cycles which provided rapidly produced prototypes at the end of each cycle, this made sure the project moved in the right direction. Since the surfaced challenges largely were related to complex mechanisms with several constituent parts, iterative development of the individual components provided results at a smaller scale, from which improvements could be made to the product as a whole. With the inclusion of rapid prototyping during the final design phase, quick design choices could be made and this ensured the best possible outcome.

The thesis presents a detailed account of the process, which includes the challenges faced and solutions adopted. The resulting auto-pointer prototype confirms the hypothesis and demonstrates the feasibility of the two actuator concept. The final prototype is able to rotate the azimuth, polarisation and elevation with only two actuators. It does this by utilising a clutch mechanism between azimuth and polarisation which disengages after the antenna has been elevated enabling the azimuth to be rotated individually. However, it is important to notice that since the purpose of the prototype was to prove the clutch as a concept, further development of the auto-pointer is needed for a final product to emerge. However, the prototype provides a reliable foundation for future work in this area. Overall, the thesis highlights the importance of a systematic product development approach in tackling complex engineering problems.

Keywords: auto-pointer, GEO satellites, antenna alignment, product development, agile prototyping, rapid prototyping, , .

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Eric Jarnestål, Gothenburg, June 2023
Staffan Staf, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ARCA	Attachment Mount
BGAN	Broadband Global Area Network
BOM	Bill of Materials
CAD	Computer Aided Design
CCW	Counter Clockwise
CW	Clockwise
DC	Direct Current
FMEA	Failure Modes and Effects Analysis
GD&T	Geometric Dimensioning and Tolerancing
GEO-Satellite	A Satellite in Geostationary Earth Orbit
IMU	Inertial Measurement Unit
LEO-Satellite	A Satellite in Low Earth Orbit
PETG	PolyEthylene Terephthalate Glycol-modified used as filament in 3D-Printing
PLA	PolyLActic acid used as filament in 3D-Printing
PRS	Product Requirements Specification
RP	Rapid Prototyping
UT	User Terminal
UV	Ultraviolet Radiation
UX	User Experience
VSAT	Very Small Aperture Antenna
2D	Two Dimensional
3D	Three Dimensional

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1

Introduction

The development of satellite internet user terminals (UTs), and consequently, antenna pointing mechanisms have been a growing research area in recent years, with many researchers and engineers focusing on developing novel designs to improve the efficiency of these systems. This thesis focuses on designs and mechanisms that aim to solve the antenna pointing process of a GEO-satellite¹ UT autonomously. Following a structured product development process, an optimal solution is chosen to create a prototype representing a minimal viable product of the antenna pointer.

1.1 Background

The proposal of the thesis project is a compact design for an auto-pointing system for a GEO-satellite application, in collaboration with Gothenburg-based Satcube AB. The project is comprised of an exploratory product development cycle, from product specification to a functioning prototype. Once developed, the prototype shall work as a subsystem compatible with an existing or future product, hence the framework of the prototype is constrained to fit the preliminary requirements set by Satcube.

Satcube is a scale-up company in the satellite communications area, founded in 2007. They develop UTs for satellite communication to enable high-speed broadband anywhere by using satellite internet technology. A UT allows the user to get internet connectivity without the need for infrastructure. In 2017, the portable satellite internet UT Satcube Ku was released, shown in figure 1.1, which provides internet through GEO-satellites. Its portability benefits the user over traditional modes of remote internet access and is therefore a great product for the segments of government/law enforcement, first responders, humanitarian aid, and broadcasting. The Ku provides three hours of connectivity with the given battery capacity. The terminal antenna needs to be oriented toward a specified GEO satellite to receive and send data.

¹ Geostationary satellite: synchronous orbit with earth.



Figure 1.1: Satcube Ku [1].

With the current product, the user has to manually point the flat panel antenna (top part in figure 1.1) toward a satellite. Setting up the device is assisted by the system itself as it tells the user how much to rotate the antenna within each axis. Although this process is a one-time setup for each use cycle, a simpler process is desired. This issue will be solved by developing a contraption for the device that will point the antenna automatically toward the satellite. This would enable the next generation of products to have a quicker and easier setup process for the users.

1.2 Aim

The aim of the thesis is to take advantage of a systematic product development process to achieve an optimal solution, capable of automatically pointing the antenna in a UT. With the extensive knowledge already available at Satcube, through their current product and previous research, a substantial foundation already exists for the conceptualisation. Using an agile prototyping approach, together with traditional conceptualisation techniques, the product development will iteratively converge toward a minimal viable product and prototype thereof, to validate the requirements.

The prototype will represent a subsystem product, replacing the manual antenna pointing process with an auto-pointing contraption, the subsystem product will here forth be referred to as the "auto-pointer". An object, representative of a real antenna, is to be pointed toward any point in the visible hemisphere, representing the position of a GEO-satellite. Apart from the aim of the thesis, elementary success criteria are also listed for prototype. In terms of functionality, the prototype should do the following:

- Align the antenna with any point in the visible hemisphere
- Maintain the alignment after the pointing process
- Mechatronic system to showcase its autonomous possibilities

One significant constraint is to design the auto-pointer with two actuators at most, as suggested by Satcube, to explore the possibility of better performing auto-pointer.

Fulfilling this requires a solution close to, if not being, a state of the art solution in the domain of innovation in product development. In the section Specification of Issue Under Investigation (1.4) this hypothesis is further described.

Additionally, the concept should be inline with the product portfolio of Satcube, and in accordance to their business idea. The developed product should ideally be easily implemented with the current or a future flat panel antenna, without redesigning the whole product, meaning that the interfacing properties need to be carefully considered. In conclusion, the thesis aims to conceptualise and develop a design for an auto-pointer, with proven functionality, as a foundation to be further developed, and possibly implemented, by Satcube.

1.3 Objectives

A product development process consisting of several adjacent and connected objectives build upon another, and consolidate in accomplishing the aim of the thesis. The objectives serve as milestones and ideally produce results and learnings to enable the following objective. Table 1.1 states the objectives of the thesis along with intended outcomes.

Table 1.1: Thesis objectives and intended outcomes.

Objective	Intended Outcome
Internal research	Learn about the current product, retrieve requirements and expected outcomes of the product
External literature review	Learn about challenges faced and results of similar development, and implementation of agile in mechanical design
Product specifications	Establish a clear description of the product and create requirements forming the foundation for conceptualisation
Conceptualisation	Generate a large amount of concepts representing a broad solution space of mechanisms
Concept evaluation	Assess the concepts and eliminate unfavourable solutions
Detailed design	Derive a complete product from the conceptual mechanism
Prototyping	Concretise the concepts or mechanisms into malleable prototypes
Testing	Assessment of the prototype according to the requirements

Additionally, since the intended aim of the auto-pointer is very clear, but the design approach being uncertain, the project provides a great opportunity to implement an agile approach. Adopting an agile prototyping approach is advantageous to quickly

assess and compare different concepts, to accelerate the development.

1.4 Specification of Issue Under Investigation

Satellites can be categorised based on their altitude. GEO-satellites are situated at about 36 000 km from the Earth's surface and have the same angular velocity as the Earth, meaning that they appear fixed at one point in the sky [7]. LEO-satellites, on the other hand, are situated much closer to the Earth, at about 160 km - 1000 km, resulting in a faster angular velocity than the Earth. Pointing an antenna toward a LEO-satellite thus requires continuous tracking of the satellite. The Satcube Ku is a GEO-satellite UT, hence the auto-pointer and the research in this thesis is focused on a GEO-satellite application.

The antenna in the UT needs to be precisely aligned with three axes to maintain an effective alignment with the satellite beam. Since GEO-satellites are in synchronous orbit with the Earth, the alignment is a one time setup for each use cycle, where-after the antenna needs to be held in place to sustain connectivity.

To be able to develop a pointing mechanism for the antenna, the first step is to recognise the three rotational axes of the antenna. The azimuth describes rotation around the Zenith² in other words, around the tripod, if it is standing upright. Normally the azimuth angle is calculated using north as a reference, as seen in figure 1.2.

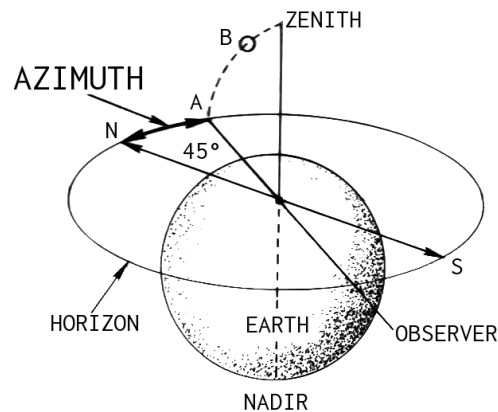


Figure 1.2: Azimuth in relationship to the Earth [2].

Elevation describes the angle from the horizontal plane of the Earth, in simpler terms; how "high up" the satellite is from the horizon. This axis is likely the most difficult to keep stationary after the pointing process since the weight of the antenna, the heaviest part of the UT, needs to be angled. Figure 1.3 depicts the elevation angle using the Earth's horizontal plane as a reference.

² Zenith - normal to the Earth's surface.

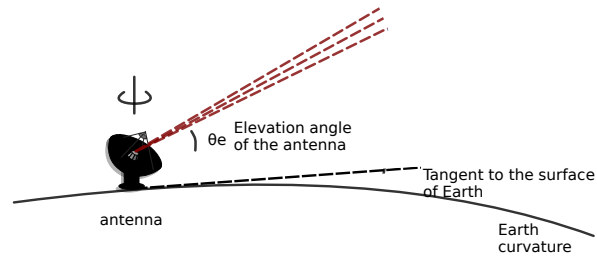


Figure 1.3: Elevation axis in relationship to the Earth and an antenna [3].

The polarisation axis describes rotation around the normal of the antenna. This axis needs to be aligned as an effect of the polarised shape of the satellite beams, which requires the antenna face to be aligned to the perpendicularity of the waves. All of the axes in reference to a figurative antenna are shown in figure 1.4.

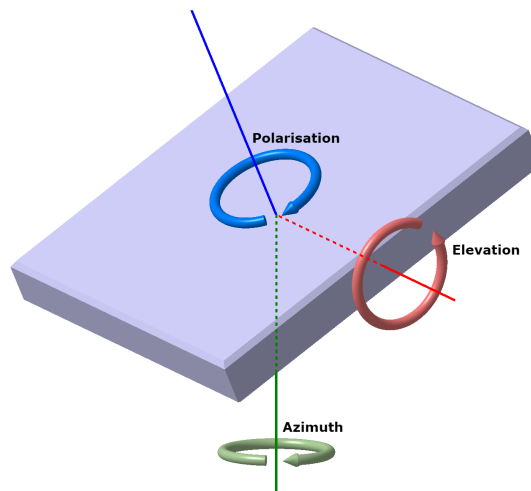


Figure 1.4: Illustration of the three axes with a rectangular antenna.
The green line represents Zenith.

The main hypothesis of the thesis is the possibility to develop an auto-pointer with two actuators for the three separate rotational axes; azimuth, elevation and polarisation. In theory, the hypothesis is supported by the Zenith paradox, which states that the azimuth and polarisation angles are the same when the antenna is pointed toward the Zenith. Simply put, the blue and green axes in figure 1.4 are aligned when the antenna is horizontal. Therefore, it should be possible to control these axes with the same actuator.

Furthermore, the auto-pointing process should be entirely autonomous, with the exception of being initialised by a user. The auto-pointer will thus for example

require a mechanism to shift the active axis of the actuator controlling azimuth and polarisation, to set the target angles sequentially.

1.5 Delimitations

An important step of the project is to clearly state its delimitations to accurately enclose the scope. These are issues that the thesis will not deal with, either because they are already dealt with or because they lie outside of the specific scope:

- The goal of the thesis is not necessarily to point the antenna toward a satellite, it can rather be explained by pointing the normal of a flat surface toward a predetermined point in 3D space.
- The antenna is presumed to have an inertial measurement unit (IMU) which correctly provides its current angles in all axes, and the target angles are given. Thus, the auto-pointer shall be able to align the antenna toward the target angles, using the current angles as input.
- Customer needs studies are usually an important factor in deciding what should be developed and are crucial to product development. However for this project, precedent user studies from Satcube have been established and have provided clear directions for the auto-pointer.
- Establishing a business plan for the product is another aspect to be left out. Plans for any conceived product idea or prototype is fully up to the company to further pursue.
- The antenna, and technology therein, is outside of the scope. Only the dimensions, weight and attachment of the antenna are required for the development of the auto-pointer.
- Although design for X [8] is an important step in any product development project, this project focuses on proof of concept rather than developing a product that is ready for the market.

To conclude, the scope of the auto-pointer is confined to the mechanism responsible for the auto-pointing process in a UT. Because of the current lack of minimally actuated pointing systems, and the novelty of autonomous pointers overall for GEO-satellite services, the thesis is an exploratory study to discover an innovative product to automate the process. All of the thesis objectives, mentioned in the objectives section (1.3), are of high importance to gather knowledge and consolidate in an innovative product.

2

Methodology

This chapter describes the methods used in the development of the auto-pointer, as well as detailing their purpose. As an effect of the imposed constraint to develop the auto-pointer with two actuators for three rotational axes, a process facilitating innovation was required. From the outset, it was evident that a creative, state-of-the-art, mechanism was required in the auto-pointer, and that there were plenty of approaches to solve it. The development and selection of a mechanism were aided by a traditional product development process, followed by an Agile prototyping phase to develop a functioning product. The combination of the two methodologies created a hybrid solution, depicted in figure 2.1.

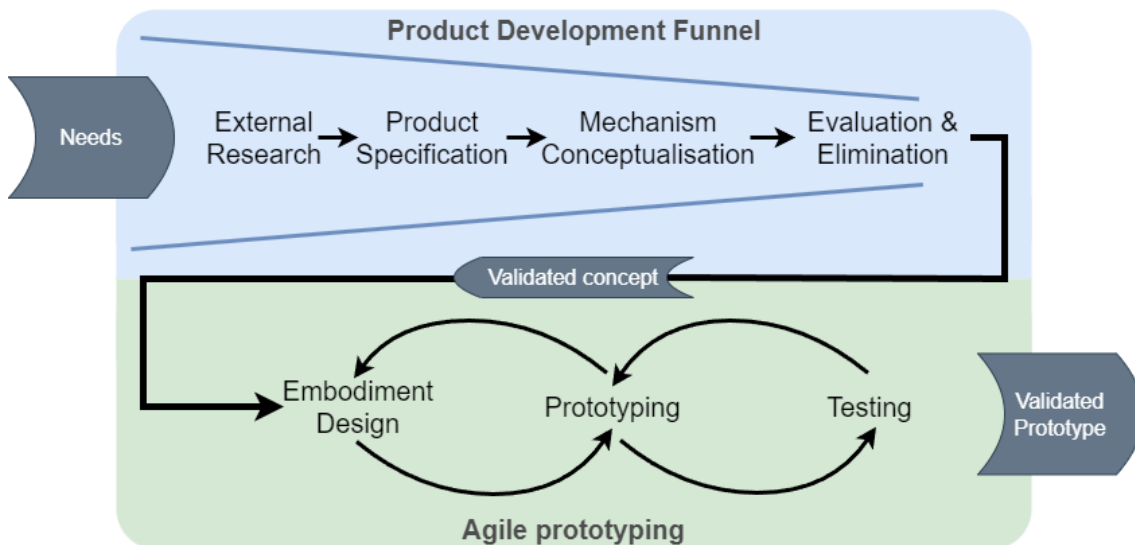


Figure 2.1: Hybrid product development process.

The top half of figure 2.1 illustrates the sequential phases associated with a generalised product development cycle. This funnel starts with the identification of needs and leads to conceptualisation and concept evaluation. The bottom half of the figure illustrates the implementation of Agile prototyping, which takes the validated concept as input and enables iterative development toward a validated prototype.

2.1 Traditional Product Development Funnel

The initial phase of the development process consisted of several carefully planned steps, derived from the book *Product Design and Development* by K. T. Ulrich and S. D. Eppinger [9]. The traditional phase gate process is widely proven to yield a broad funnel of concepts and uses systematic processes to narrow the funnel toward optimal concepts. By compiling the constituents of the processes leading up to concept evaluation, an outline for the methodology applied to the thesis was formed:

- External research (literature review) - aim to gain knowledge about the field of study, as well as investigating if any similar principle already exists to possibly gain inspiration for further development.
- Product specification - translate the needs into requirements for the product, and construct a specification which serves as a framework for the development. The specification is later revisited for the validation of the final outcome.
- Conceptualisation - an innovative brainstorming phase to create concepts based on the previous research and specification. The goal is to cover the entire solution space with multiple unique concepts.
- Concept evaluation and elimination - in this step different designs are presented and are evaluated against the criteria in the specification using concept-selection matrices.

Because of the nature of the problem statement, there was a wide range of unique solutions to the mechanism required for antenna pointing. Therefore, it was deemed most appropriate to utilise the traditional product development funnel purely for the rotational mechanisms in the auto-pointer.

Following a good foundation in research and a product specification sheet, the concept generation phase focused on brainstorming alternatives for the mechanism enabling the auto-pointing capabilities. The processes for concept evaluation work best with a wide range of concepts, from which the concept screening and selection could be applied. This methodology provided a reliable process to achieve an optimal concept for further development.

2.2 Agile Prototyping

Agile, which is a common strategy that is often found in software development, can also be implemented in other domains of product development. In many aspects of the mechanical design and/or product development, the implementation of agile has many good examples of success [10][11]. However, for some parts of the development process, such as prototyping, it has not yet been fully explored and evaluated. This is not surprising as a key aspect of agile is to output functional features after every cycle, meaning that some clever adoption is required for hardware development.

The output of the funnel in figure 2.1 was a solution scope narrowed down to one concept. Agile prototyping was deemed an applicable method to elaborate on the chosen conceptual mechanism, and derive a product from it. Since the previous conceptualisation solely focused on the mechanism of the product, the functions of the product were established, which provided a smooth entry to the first embodiment design. Where-after the design was iteratively improved using multiple design cycles. The steps included in the iterative Agile prototyping phase were:

- Embodiment design - to better visualise and evaluate the different designs, detailed CAD models are created. This aids in finding improvement and the decision of which designs to continue developing.
- Prototyping - prototyping is a tool to further concretise and evaluate a design, and is especially helpful once it is difficult to find areas of improvement in the digital design.
- Testing - testing the prototypes assesses functionality of the product, validates requirements and may give points for further improvement.

The Agile approach enabled a flexible work-flow, to quickly improve the design of the product. Because of the time-limitation of the thesis, the amount of design-sprints was limited. However, since every sprint ended with a feasible design, there always existed a design ready for prototyping. Meaning that the time limitation did not have as severe consequences, it rather affected the performance of the prototype. Thus, the Agile methodology enabled an effective path toward a minimal viable product, with performance based on the amount and quality of design-cycles fit to the time-frame.

3

Development Process of the Auto-pointer

The development of the auto-pointer serves as an authentic product development project, hence the development process is essentially the core of the thesis. This section provides detailed summaries of the important systematic approaches adopted during the project. Some results are used to contextualise the processes, nonetheless, all of the main results are presented in detail in the results chapter.

Initially, a literature review was conducted, which generated extensive knowledge supporting the development. Thereafter, the project was divided into systematic phases, representing a traditional product development funnel, concluding into a concept selection. Toward the final design phases, Agile methodologies were implemented, resulting in short development cycles to iterate and actively generate new knowledge from the product designs. Knowledge gained from each iteration was input for the next iteration, to ensure every cycle yielded an improvement over the previous one.

3.1 Literature Review

The development of satellite internet UT:s and antenna pointers has been an active research area in recent years, with many researchers and engineers focusing on developing novel designs to improve the efficiency of these systems, as a result, plenty of literature and patents exist in the domain. However, since there are several approaches to designing an antenna pointer, both manual and automatic, this literature review will focus on designs and mechanisms that aim to solve similar alignment autonomously. It is also important to note that multi-axes alignment exists in products outside of satellite applications, thus reviewing similar mechanisms outside of the domain had the potency to add constructive knowledge.

3.1.1 Similar Products

In the search for similar products from competitors, the first aspect to acknowledge was the categorisation of satellite technologies used in this field. The two main categories are BGAN (Broadband Global Area Network) and VSAT (Very Small

Aperture Terminal). BGAN terminals are generally smaller in size, require less accurate pointing but at the cost of a low bandwidth, whereas the more novel VSAT requires accurate pointing but enable an immense increase in bandwidth [12] [13]. Additionally, VSATs are experiencing a shift from parabolic dish antennas to more compact flat panel antennas, which enables VSATs to close the gap in size difference compared to BGAN terminals [14]. BGAN terminals still occupy the majority of the market, but with the continuously increasing demand of satellite internet and advancements in VSAT technologies, the VSAT versions are expected to experience stronger growth [15]. The Satcube Ku utilises VSAT technology, although its compact size. Table 3.1 lists examples of UTs with VSAT technology, and auto pointing capabilities.

Table 3.1: Table showing examples of auto-pointing VSATs.

Terminal Name	Auto-pointer	Weight	Research takeaways
Satcube Ku	No	8 kg	(Reference), Flat panel antenna
Toughsat XP .98M Flyaway Satellite System (0.98 m dish) [16]	Yes	56.7 kg	<3.5 minutes pointing time, 3-axis motor drive, Manual override, IP-66 rated, Parabolic dish antenna
Cobham EXPLORER 6075 LX [17]	Yes	42 kg	<4 minutes pointing time, 2-axis motor drive, Manual override, 4 axis-symmetric reflectors instead of polarisation pointing, Parabolic dish antenna
C-Com iNetVu Ka-75V 75cm Ka-Band Drive-Away Antenna [18]	Yes	52 kg	<2 minutes pointing time, 2-axis motor drive, Auto polarisation switching, Parabolic dish antenna
Starwin Flat Panel Auto terminal FL60P-E [19]	Yes	20 kg	<3 minutes pointing time, 3-axis motor drive, Flat panel antenna

Notable is that all of the UTs in the table are so-called flyaway VSATs, meaning they are categorised as lightweight, portable and can be brought onto commercial flights, in some cases by carrying them in multiple packages [16]. As a result of the technology decreasing in size, the market trend is moving more toward mobility in UTs [20]. An additional market trend is the implementation of auto-pointing capabilities, with several of the major companies implementing fully motorised "one-button" or "auto-deploy" solutions, either in their flagships or as derivative products [21] [22].

3.1.2 Inspirational Mechanisms

With the knowledge of the competitors' products and their implementation of auto-pointers, the next target was to find existing products on the market, that in theory could solve, or help to solve, the initial problem presented in this thesis. The objective rapidly changed into finding mechanisms that could give inspiration for further development of the axial alignment required in an auto-pointer. One of the difficulties of this part of the literature review was to not rule out anything too quickly, and not to confine the search strictly to mechatronics and satellite technology. During the review, many different mechanisms were discovered, and the most important ones are listed in table 3.2, and figures of the mechanisms are appended (A.1).

Table 3.2: Table of useful mechanisms.

Useful mechanisms designing with n-1 actuators for n joints	
Mechanism	Advantage
One-way bearings	Two axis rotation in one direction and single axis rotation in the other
Limit bearing	Two axis rotation when in contact and single axis rotation in contact-less interval
Clutch	Two axis rotation when engaged and single axis rotation when disengaged
Cardan joint	Translation of rotation through elbow
Differential gear box	Multiple cases of output rotation depending on input rotation
Spherical gears	Output rotation throughout the surface of the gears, which enables designs of active ball joints or spherical differential etc.
Gyroscope	Supports rotation in two to three DoF
Worm Drive	Enables high output torque without back-driveability

Perhaps the most interesting of the discovered mechanisms, was the worm drive. The utilisation of a worm gear and a worm wheel enables high gear ratios with minimal backlash. The high ratio translates into higher torque, which enables high precision due to the lower output rotational speed. The gear ratio of worm driven mechanisms are easily calculated; the worm gear has the gear ratio of 1, and the ratio of the worm wheel is equal to its number of teeth. With a worm wheel consisting of 40 teeth the gear ratio will be 1:40, which means that for every rotation of the worm wheel, the worm gear has to turn 40 times. Further more, the worm drive transmission can be designed in a way that enable a non-backdrivable joint [23]. Since an important aim for the auto-pointer is that the mechanism should maintain its position after pointing, and preferably by consuming no power, this mechanical locking ability was highly valued.

Whilst in the search for similar mechanisms, there were mechanisms that were dif-

difficult to understand from text or pictures alone. To understand the mechanisms, rapid prototyping was utilised and the mechanisms were created in CAD, and in some cases 3D-printed. Additionally, kinematic videos of mechanisms proved to be another great source of inspiration, and provided insight about the mechanisms before being implemented into concepts or evaluated by 3D-printing [24].

3.1.3 Reducing Actuator Amount

The prefacing hypotheses, from which the thesis originated, is maintaining functionality while utilising fewer actuators in the design. The traditional design for any type of axial alignment device has at least n actuators for n joints, which raised the question on why reducing the actuator amount, when possible, is not a common practice in mechanical design. Existing research on this subject was helpful to validate the thesis itself, through validating the requirement of having two actuators in the design of the auto-pointer.

Minimally actuated serial robots are one case where the goal is to mimic the functionality of hyper-redundant robots¹ without the actuator redundancy [25] [4]. The snake-shaped robots are actuated by a mobile actuator, traversing the snake's joints, instead of actuating each joint by one separate fixed actuator (figure 3.1). They are claimed to have advantages in simplicity, smaller weight, higher energy density, lower cost and better modularity compared to hyper-redundant robots. On the other end, the obvious disadvantage is the time it takes to actuate all of the joints sequentially, which also leads to an oscillating path of the end defector. When comparing the error of the minimally actuated robots with fully actuated robots, the result is significantly worse paths, but surprisingly low errors in end positioning, making them viable for pick and place operations in applications where weight and low actuator amount is beneficial, such as space exploration [4].



Figure 3.1: Minimally actuated serial robot [4].

Wearable exoskeletons used in medical applications and for sports rehabilitation is another extensively researched application where, in some cases, the amount of actuators is preferred to be reduced [26] [5]. Minimally actuated exoskeletons facilitate

¹ Robots with more degrees of freedom than necessary to accomplish their tasks, which allows them to navigate complex and constrained environments.

the user's gait cycle² by actuating knee and hip rotation simultaneously, using only one actuator per leg (figure 3.2). This is possible due to the bi-articular coupling of hip and knee rotation in the gait cycle, allowing a mechanism to simultaneously rotate a knee and hip using only one actuator. The reason to use one actuator for the two joints instead of one per joint is motivated by the importance of low-weight exoskeletons according to user studies [27]. Researchers claim that minimally actuated exoskeletons weigh less and cost less to produce [26] [5].

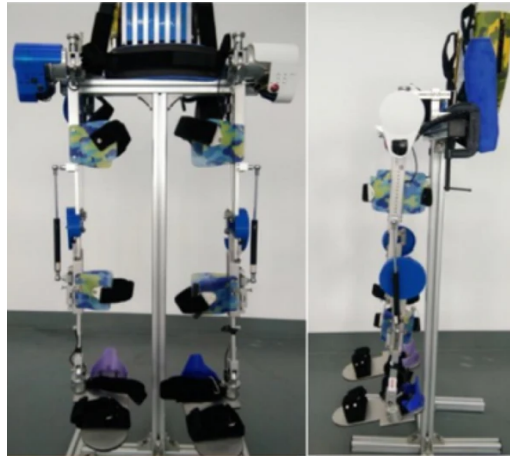


Figure 3.2: hip-knee exoskeleton [5].

Generally, a product's rate of failure can be calculated as the sum of the failure rate for each individual component [28]. This is an important aspect when considering the parts count in an electronic device, and promotes designs that use fewer components when possible. The two aspects of parts count is either having redundancy, which allows certain components to fail without compromising functionality, or reducing the components to a minimal level without any redundancy. Additionally, if a component has a multipurpose usage, such as actuating two joints with one actuator, the component-level failure rate remains.

In conclusion, the literature review on reducing actuator amount seems to consolidate in lower weight, cost and complexity in products designed with fewer actuators. However, this comes at the cost of slower mechanisms and, in some cases, lower precision. Apart from further endorsing a design with two actuators in the auto-pointer, the findings were important to get a better understanding of the trade-off inherent to actuator reduction, which later alleviated the evaluation process, especially for comparing two-actuator concepts to a three-actuator concept.

3.1.4 Agile Prototyping in Mechanical Design

The Agile methodology consists of several principles and values that aim to help development processes with agility and adaptability [29]. Agile is a project management principle and has been widely practised in the software industry. When

² Movement pattern of the legs while walking or running.

applied, the team should work in very short development cycles, sprints, to create a fully functioning product. The product will then, at the end of these sprints, be demonstrated to the stakeholders. Because the expected results, a functioning product after each sprint, it is understandable that agile is more common in software development than hardware design.

This is challenging in hardware development because a product is likely not ready to be used or evaluated mid-development. Therefore the sprint cycles have to be redefined to focus more on delivering results to learn from after each cycle. So that at the beginning of every new cycle, there is some newly acquired result or data that can be used to improve the last developed product. Agile in hardware development can be seen as an attempt to quicken the process of achieving a minimal viable product, and especially if the product is comprised of several functions, the team should focus on sub-efforts within the larger scope of the product [30].

One of the underlying aspects that make agile in hardware development different compared to software development is that software practically costs nothing to copy and is instant, in comparison to hardware prototyping which requires physical materials and manufacturing time. B. Cliff et al. acknowledges the need for a local development setup for agile hardware development, similarly to local development of software, but using tools such as virtualisation for design and 3D-printing for prototyping [31]. The aim is to reduce costs and effort required for the iterative sprints, to achieve accelerated results. B. Cliff et al. also mentions that for Agile to work with complex multilayered products, the subsystems of a complex product should be divided into smaller-scale products, to which an agile methodology is easier to implement.

In summary, agile is widely practised in software development and not as much in hardware design. This might depend on different achievable sub-goals of the different processes. However, with some minor adjustments agile brings benefits to hardware prototyping as well.

3.2 User Terminal Needs Analysis

Conversations with the sales team at Satcube revealed that the three main ongoing talking points at satellite internet fairs and other customer meetings, regarding GEO UTs, are; portability, auto-pointing capabilities, and usage of the Ku-band in satellite beams. The portability aspect reflects that the users of satellite internet desire more compact solutions that can easily be brought to remote areas, as an effect of the technology mostly being used in areas without traditional internet infrastructure. The auto-pointing aspect is related to the desire for a simpler setup process. Portable UTs with manual setups, like the Satcube Ku, incorporate UX design to deliver intuitive operation for the users, which might be challenging. The drive toward "one-button" solutions, discovered in the literature review, is an attempt to replace the need for intuitive UX design, as they are advertised to provide seamless setup processes. The usage of the Ku-band is likely related to users' need for faster

bandwidth, as the high-frequency Ku-band enables higher throughput than for example the L-band, often used with BGAN technology. All of these points align with the findings in the literature review (3.1.1), which shows the direction of the market trend, and reflects the requirements for new UTs.

One drawback with the addition of an auto-pointer to portable UTs is that the end product undeniably becomes larger and heavier than a manual version. This presents a trade-off for users, where they have to choose slightly bulkier products if they desire the auto-pointing capabilities, which seems acceptable by users considering the prevalence of auto-pointing products on the market. However, this trade-off is mitigated by developing more compact auto-pointing subsystems, which in the end could become the new standard on the market.

A customer needs study has previously been conducted by a project group from Chalmers University of Technology, with possible users of LEO-satellite internet terminals as the target audience. Although the use cases for the internet through LEO and GEO technologies may differ, there still exists a significant desire for portable terminals for both applications. The results of both the interviews and the survey are in the appendix [A.2] [A.3].

In conclusion, the needs for an auto-pointer in a portable UT could be divided into two categories. Firstly, it needs to be easy to use, via a "one-button" solution or similar. Otherwise, there exists no justification to replace an intuitive, manual pointing process. Secondly, to comply with the market trend, and to minimise the trade-off of a bulkier product, the auto-pointer needs to be as compact as possible, and still maintain functionality.

3.3 Auto-pointer Specification

In any product development project, it is crucial to have clear product requirements which describe what the product should do. In most cases, to ensure the product's attractiveness, the requirements should be derived from customer needs, which enables the product to satisfy those needs [32]. Regarding requirements for an integrated product or subsystem, such as the auto-pointer, the requirements for the interface to the supersystem are highly important to maintain the compatibility and viability of the product as a whole.

The requirements of the auto-pointer were derived from the needs of the stakeholders at Satcube, namely the engineers and sales team, who have previously identified the needs of the end-users. Together with Satcube, the functional product requirements were established. The generalised requirements for the auto-pointer, agreed upon with the company, formed the foundation for the auto-pointer:

- The auto-pointer shall be able to point the antenna at any point in the sky
- The process of pointing the antenna toward given coordinates shall be completely autonomous

- The auto-pointer should ideally consume no power once target angles are achieved
- The auto-pointer should meet the dimensional and weight requirements that exists to ensure a compact design
- The prototype should utilise a mechatronic system that showcases the autonomous capabilities of the system

Regarding the interface of the auto-pointer to the UT, the following constraints were imposed by Satcube, and were regarded in the development:

- The auto-pointer shall be mounted on a tripod-style stand
- The mechanism needs to be attached to the antenna with the given attachment (ARCA³ type)

Following a product requirements specification process (PRS process), the requirements were turned into a more detailed specification, better fit to guide the product development [33]. It is based on the fact that customers or other stakeholders know what the product should do, whereas the developers must turn this information into metrics that can be used in development. Additionally, the specification should also serve as a foundation for validation of the product in the later stages of development, by testing the product or prototype in association with the defined metrics.

The complete product specification for the auto-pointer was achieved by quantifying the generalised requirements from Satcube, and adding appropriate metrics within four categories; physical properties, product architecture, operation performance, and operation conditions. The specification is shown in table 3.3.

Table 3.3: Product specification sheet.

Category	Metric No.	Metric	Units	Marginal Value	Ideal Value
Physical properties	1.1	Weight	kg		<2
	1.2	Stowing volume	mm		<440x330x60
	1.3	Actuator amount	No.		<3
Product architecture	2.1	Terminal attachment type	type		ARCA
	2.2	Terminal mounting time (onto attachment)	s		< 30
	2.3	Anchoring System	type		Tripod
	2.4	Auto-pointer tripod manufacturing cost	\$		< 1000
Operation performance	3.1	Azimuth range	° (degrees)	± 180	± 360
	3.2	Elevation range	° (degrees)	[10, 90]	[10, 170]
	3.3	Polarization range	° (degrees)		± 90
	3.4	Azimuth precision	° (degrees)	± 1	± 0.5
	3.5	Elevation precision	° (degrees)	± 1	± 0.5
	3.6	Polarization precision	° (degrees)	± 3	± 1
	3.7	Auto-pointing time in all axes	s		< 60
	3.8	DC voltage	V		24
	3.9	Power draw once target position is achieved	W		0
Operation conditions	4.1	Operational ground inclination	° (degrees)		< 10
	4.2	Operational temperature range	° (celsius)		[-20, 55]
	4.3	Operational in sporadic wind gusts	m/s		< 20
	4.4	Operational in continuous wind speed	m/s		< 10

³ Attachment clamp with screw fastener, commonly used with bi- or tripod applications.

3.3.1 Justifying the Specification

The specification was derived from the needs analysis together with Satcube's requirements. With the existing Satcube Ku, some of the metrics were easily justified. Automating the antenna pointing process does not change the metrics in terms of operational performance and operational conditions. metrics 3.1 to 3.6 (table 3.3) are equally crucial in the auto-pointer compared to the already validated manual product to ensure full coverage of the hemisphere and to sustain connectivity with the satellite beams. For these metrics, "marginal values" were added, representing the threshold for minimal functionality, whereas the ideal values are preferred. The same idea applies to metrics 4.1 to 4.4, considering real use cases of the Satcube Ku, and the environment that the product may be used in.

Considering the needs analysis (3.2), metrics regarding the weight and size of the auto-pointer were critical to minimise, and therefore the values were set as low as possible. Metrics 1.1 and 1.2 received their ideal values based on what was thought attainable while being adequately low. Metric 1.3 regarding actuator amount, however, was more intricate and could not be directly tied to the needs analysis. The requirement of designing the auto-pointer with two actuators was imposed by Satcube and was rather considered to be an exploratory study to determine if it enables a more lightweight or compact solution. Similar to the implications from the research on minimally actuated systems (3.1.3).

In conclusion, the ideal values of the metrics were not necessarily to be seen as targets, but rather an attempt at setting probable margins. The initial study of the current product and conversations with engineers and the sales team at Satcube revealed which criteria were the most valuable. And the auto-pointer aimed to minimise these, such as weight, size, pointing time, and maximising precision, while staying inside the set margins was deemed to yield a satisfactory product.

3.3.2 Functional Decomposition

Although the requirements and product specification make a great foundation for the conceptualisation, a simplifying problem decomposition, shown in figure 3.3, was made to visualise the functions of the auto-pointer. The different domains of the functions were categorised in the figure by colour, blue is software related, yellow is electronics and the green functions represent the mechanisms required to obtain the axial rotations. In combination the three categories form the mechatronics system of the product. Moreover, the function diagram spotlights the main functions that were essential to be considered in conceptualisation. Both software and electronic related functions rely upon the design of the mechanism, thus it was clear that the green functions were focal points in the conceptualisation stage.

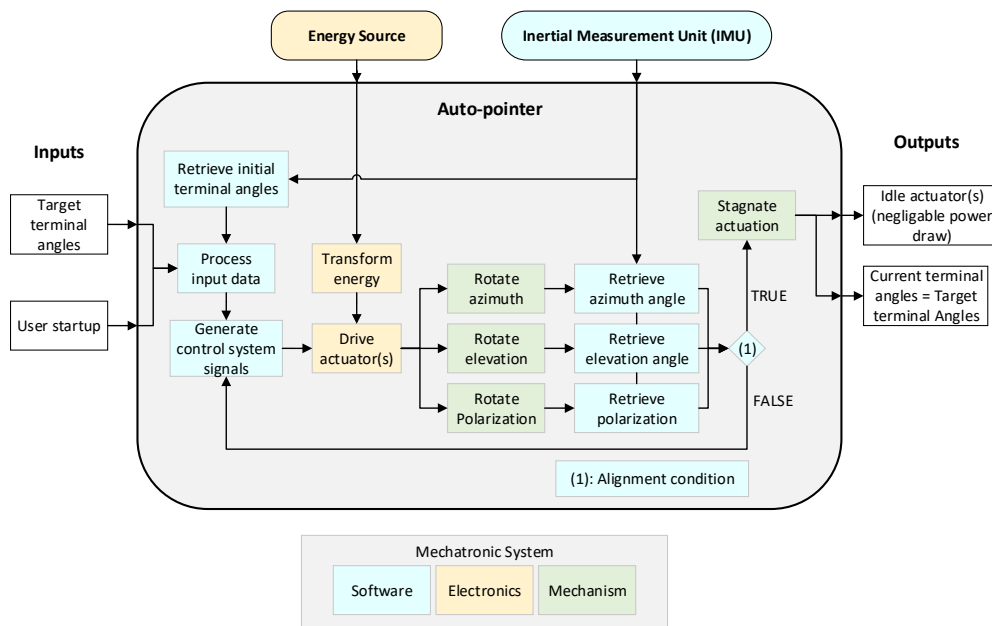


Figure 3.3: Function diagram of the auto-pointer.

3.4 Conceptualisation Phase

With the knowledge gained from reviewing literature in combination with clear product requirements and a functional decomposition, a valid foundation was established for the conceptualisation phase. The aim was in short to design a compact contraption which uses two actuators to point the antenna at any point in the sky. Initially, it was clear that designing the auto-pointer with $n-1$ actuators for n joints required some kind of mechanism replacing the n :th actuator. Subsequently the conceptualisation could be structured by category early in the brainstorming phase. The different categories of possible solutions or helpful mechanisms were derived from reviewing literature on mechanisms, similar applications in other products and intuition. The table of mechanisms found in the literature review (table 3.2) was very useful to derive concepts from, as some of the mechanisms in the table could be potential solutions for the functions established in the function diagram. At this stage a systematic method, like a morphological matrix, was considered to be used [34]. However, it was deemed very difficult to implement, as the mechanisms could not simply be combined into functioning concepts. Instead, the concepts were derived from inventive brainstorming, both in individual and group sessions, and related stimuli was used in the form of kinematic animations and 3D-printed parts [9].

The aim of the brainstorming was to explore a large quantity of possible solutions, hopefully reflecting the entire solution space. With the discovered mechanisms, multiple concepts were derived from each one or a combination of several, and sketches were made to be able to document them and convey their functionality. As a result of the mechanisms being somewhat difficult to convey in 2D-sketches, rapidly

prototyped 3D-prints were deemed a convenient form of stimuli to the brainstorming work.

3.5 Elimination Process

In the elimination process, multiple proven methods assist with identifying the best concept, following a standardised product development Funnel [9]. The concept-selection matrices used were an elimination matrix, a Pugh matrix and a Kesselring matrix. These methods are designed to grade the concepts in various ways and therefore objectively present which of the concept fulfils the requirements best.

The initial step of the elimination process is to assess viability of the concepts, by utilising an elimination matrix. The elimination matrix assesses if the concept fulfils all of the main functions, if not, they are removed for the next step.

Secondly, a Pugh matrix was applied to the remaining concepts after the elimination matrix. In the Pugh matrix, all concepts were compared to a randomly selected datum concept [35]. The concepts are then graded depending on their comparative performance for each requirement to the datum concept, which yields a rank based on their overall performance. Randomly selected datum concepts were graded against, in three iterations of the Pugh matrix. Because Satcube communicated that some requirements were more important than others, it was decided that weights should be incorporated in the Pugh matrix as well. This would ensure that the concept which scored better in the most important metrics was graded higher. Once the concepts had been ranked in the Pugh matrices, the choice was made to insert a cut-off point to keep the best performers. Since there often is a problem with Pugh matrices and that the process can be biased a Kesselring matrix was utilised. If the Pugh matrices was correct the result of the Kesselring would endorse these results and portray the best concept simultaneously, providing the best concept for further work and redundancy for the elimination process.

Before the Kesselring matrix could be utilised, the requirements needed to be weighed. In this grading process, all requirements are compared to one another in a weight matrix, for each comparison, if one requirement is deemed more valuable than the other it receives a 1 and the other receives a 0, if they are of similar value they both receive 0,5. After the grading process, a relative relevance number is calculated for each requirement and a ranking system of the requirements was obtained. The results of this stage were straightforward to communicate to the stakeholders at Satcube, to find out whether the company agreed with the rankings.

Finally, a Kesselring matrix was used to identify the most relevant concept of the remainders. In this matrix, each concept received a grade on a scale of 1 to 10 for their performance within each requirement, where the relative relevance number of the requirements was applied as a multiplicative factor [35]. By adding all of the concepts' relative scores, a final ranking was obtained, after which the highest-graded concept was deemed the best to continue developing.

3.6 Agile Prototyping

Following the elimination process there was a conceptual mechanism as a base for the Agile prototyping phase. During this phase, the focus of the cycles was to acquire new information that could be implemented in the next development cycle. It would also prove to enable a quicker progression toward the design of the final prototype.

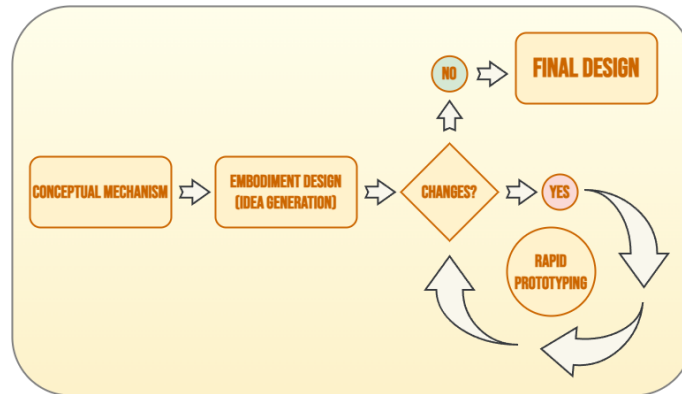


Figure 3.4: Illustration of the agile prototyping process.

Figure 3.4 illustrates the work-flow of Agile prototyping, tailored to the development of the auto-pointer.

Concurrent engineering, used as a compliment to agile prototyping, was one other aspect that greatly increased the efficiency. Furthermore, the time of development during the conceptualisation phase, embodiment design, detailed design and final prototyping could be decreased due to higher efficiency. The strategy was to work in parallel and develop similar or different products, concurrent, where-after retrospective meetings were made to analyse differences or to join the developed solutions. The method allowed for new knowledge, boosted progress and quicker progression which in turn led to a better final prototype.

3.6.1 Rapid Prototyping

As quoted by S. Upcraft and R. Fletcher "RP is a generic term for several technologies that enable components to be made without the need for conventional tooling in the first instance or indeed without the need to engage the services of skilled model-makers" [36]. Meaning, there are multiple techniques to create complex components fast and without the need for trained professionals. This leads to shorter lead times within the prototyping process and cheaper manufacturing which is very important for prototypes since they might not be used at all.

During this development project, prototyping was a very important process to better understand the designs and identify their weaknesses, also it was an enabler of the Agile prototyping approach. 3D printing was the most accessible, therefore it was

used as the rapid prototyping process. The amount of manufactured parts for this project had not been viable to manufacture in another way, it would have been too expensive. Also, being able to evaluate the design just hours after starting the manufacturing was important to be able to move forward. This method also encourages creativity as one failed prototype is not a problem because it is not heavily invested in, neither with time nor money. The rapid prototyping process utilised in this project is shown in figure 3.5.

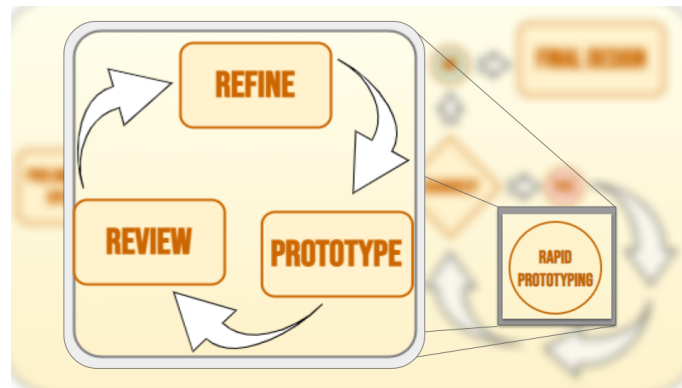


Figure 3.5: Illustration of the rapid prototyping process.

3.6.2 3D-Printing

The majority of prototypes throughout the project, ranging from stimuli in the brainstorming phase to components for the final design, were 3D-printed. 3D-printing, which is a means of additive manufacturing, allows for highly complex object and could be used to better understand the different mechanisms [37]. For example, the translation of rotation and forces in gearboxes is complex to grasp without previous experience. Having the gears physically at hand, simplified further development and research. Furthermore, iterating the development process with 3D-Printing enabled work closer to the concepts, making it easier to evaluate and improve their designs.

Everything was printed in PLA because of its ease of use, as well as low failure rate when printing. However, PLA is very brittle and an argument could be made to use PETG which is more versatile due UV resistance and higher tensile strength for example. However, since the goal was to produce a working prototype as a proof of concept, reliability was valued higher. Instead, a higher infill was used in the PLA printed parts, 50% instead of the regular 15%, this made the PLA prints more durable, but taking slightly longer time to print.

All of the 3D-printing was done in an Ultimaker S5 or Ultimaker S3, the S5 has a much larger print area than the S3 and thus was used to print larger pieces or if multiple pieces needed to be printed at once. However, because of the larger build plate some reliability issues was noticed and in some rare occasions prints could rise from the build plate and deform. Acquiring this knowledge early enabled the more important prints to be printed on the S3 which always resulted in the expected print quality. There were also several Prusa i3 MK3s+ available, used for some prints in

the earlier phases, however these were even more unreliable and therefore not used as much later in the development.

3.6.3 Prototype Testing

Prototype testing was an essential aspect to leverage knowledge from the prototypes created throughout the project. Studying the physical prototypes generated information about their effectiveness associated with the predefined requirements. Additionally, it was important to use prototypes as a means of communicating results to the stakeholders at Satcube to get feedback from an invested third party.

Since rapid prototyping was adopted throughout the development, the testing had different purposes depending on what stage the prototype was situated in. For the early 3D-printed mechanisms, the aim was solely to learn about their functionality, such as degrees of freedom and back-driveability, to assess their integration into concepts. Whereas, later prototypes were tested with the requirements in mind, to assess the viability of the product in its wholeness. At this stage, requirements on precision, size, and implementation of mechatronic components were some of the focal points. In conclusion, continuous physical evaluation of the prototypes was one of the key enablers of the Agile approach in this project.

3.6.4 Failure Modes and Effect Analysis

The Failure Mode and Effects analysis (FMEA) is a systematic and proactive approach to identifying potential failures, their causes and the potential effects they may have on a system or a process. FMEA is a popular tool and is both widely known and used in various parts of the industry, and it should preferably be applied from the earliest conceptualisation stage and be used continuously throughout development [38]. There are two steps to the process of FMEA analysis, the intention of the first step is to identify the failures and their effects. The intentions of the other step is then to analyse and determine the severity of the different failures. In this project, an FMEA proved to be advantageous as a development tool to find possible flaws with the prototype, and to mitigate them through the findings of the analysis. Thus, it was conducted after the concept elimination, since the potential failures would likely have been concept-specific.

3.7 Detailed Design

The design of a market-ready final product laid outside of the scope for this project, however, a detailed design of the final prototype was constructed and evaluated. This design was the result of the applied Agile prototyping and was constructed with rapid prototyping, similarly to the method used in the conceptualisation for the different mechanisms. The difference during the detailed design phase is that only one concept was refined iteratively instead of creating several prototypes with the goal of comparing concepts. Every design was evaluated during the development process, some of the designs were re-iterated directly and some were evaluated after

3. Development Process of the Auto-pointer

development. To evaluate the finished designs, they were 3D-printed and underwent a physical evaluation, this enabled better understanding of the mechanisms and improvements could be realised.

The fundamental objective of the detailed design was to connect all of the elements in the remaining concept, and design a minimal viable product. Therefore, aspects that were not obvious in the conceptualisation became focal points in the detailed design. This includes; fixtures for the machine elements, material choices, water proofing, design of the mechatronic system and design for assembly. The development process from the first sketch to the last prototype is described in detail in the results chapter.

4

Results

This chapter elaborates and describes the results of the methods used during this project. It will present the different concepts and the evaluation processes used to choose the final concept. Then it presents the results of the Agile prototyping phase of the final design, and the chapter is concluded with an evaluation of the final prototype.

4.1 Concepts

In this section, the different concepts will be presented. To mechanically lock all axes after the antenna has been aligned, all of the concepts will include a worm gear and worm wheel with all the actuators. This is because worm gears can be designed in a way that it is non-back-drivable, thus when the actuators are not producing torque on the worm gear, the axis will be locked in position. This enables mechanically locked mechanisms, without having to utilise separate actuators to engage and disengage brakes, which would add unnecessary weight and complexity. If this is not the case, the description of the concept will specifically state that another way of locking the axis is present.

4.1.1 Concept A - Three Actuators

Concept A utilises three actuators, all directly connected to the axis they control, this concept is used for the intended purpose of being a datum concept in the elimination process. One of the constraints from Satcube was to only use two actuators in the design, otherwise, the obvious concept would have been to utilise three actuators. One actuator for each of the three rotational axes because that design would have a higher probability of delivering the best accuracy in every axis. This concept was used in the different elimination processes that were conducted in this project to objectively prove that this design with three actuators was not outstandingly better than the other designs with two actuators.

4.1.2 Concept B - Clutch

Concept B utilises two actuators, one actuator is directly connected to the azimuth axis and one actuator is directly connected to the elevation axis. The polarisation

axis is connected to the azimuth axis via a clutch mechanism which will engage and disengage depending on the elevation angle. Therefore the actuators must run in a specific sequence for this concept to work. The mechanism will start to rotate polarisation and azimuth together, when the polarisation is at the correct position it will stop and the antenna will start to elevate. After the clutch has disengaged, fully, the azimuth can simultaneously be set by the other actuator. The clutch concept, in its folded and elevated position, are visualised in figures 4.1 and 4.2.

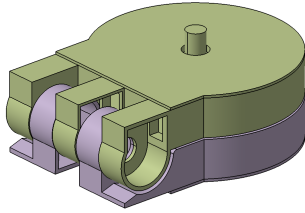


Figure 4.1: Concept B.

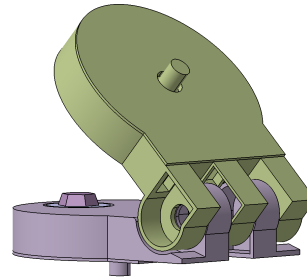


Figure 4.2: Concept B.

4.1.3 Concept C - One-way-bearing Kardan

Concept C was designed around a one-way bearing portrayed in figure 4.5. One actuator is connected to the elevation angle and one actuator is connected to both azimuth and polarisation via a cardan-joint, as seen in figures 4.3 and 4.4. This enables a connection between the two non-reliant on the elevation angle. The one-way bearing will allow both azimuth and polarisation to rotate in one direction but only one in the other direction. This concept has to deploy in a specific sequence to work properly, first, it will rotate azimuth and polarisation in one direction until the azimuth is set, then it will rotate in the other direction to set the polarisation and then it will be able to set the elevation. To retract it will also have to execute in a specific order, first elevation, then rotate azimuth to zero and then rotate polarisation the opposite way to ensure any cables are not under any stresses. One obvious downside of this mechanism is the backlash in the bearing, when it has disengaged and shall engage again the gap between the beginning of the rotation and until it rotates both axes is not always known.

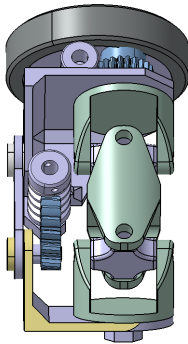


Figure 4.3: Concept C.

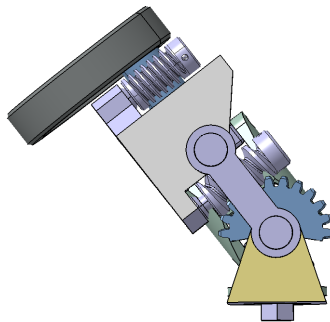


Figure 4.4: Concept C.

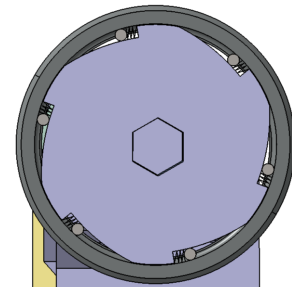


Figure 4.5: Closeup of spring-loaded one-way bearing.

4.1.4 Concept D - Limit-Bearing Kardan

Concept D works in the very same way as Concept C, the difference is that the uncertainty after disengagement is removed. This works by having a mechanism that only engages in one specific point, a limit bearing. This means that there is a clearance but it is designed that way that allows the system to know the gap at all times. The limit bearing has two notches, allowing the azimuth and polarisation to rotate together when the notches are in contact (see figure 4.7), and between the notches there is a 180-degree window enabling either azimuth or polarisation (depending on configuration) to rotate separately. The negative aspect of this mechanism is that azimuth and polarisation can not be exactly the same. However, the sequences of execution are the same as in concept C. Additionally, concept D utilises a linear actuator for the elevation axis instead of a worm-wheel driven DC-motor. In theory, both methods work similarly and thorough research would be required to find out which performs the best, thus the concept evaluation prioritised the differences in the main mechanisms instead. In this case, the limit-bearing. A conceptual design of the concept is shown in figure 4.6.

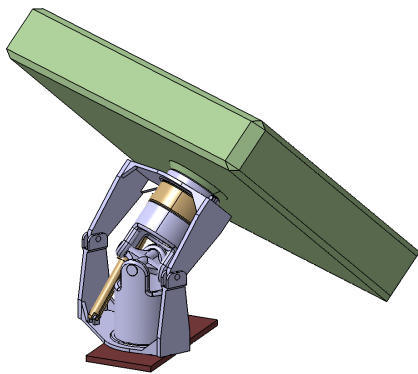


Figure 4.6: Concept D.

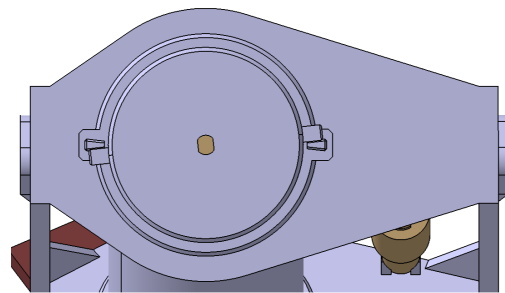


Figure 4.7: Closeup of conceptual 180-degree limit bearing.

4.1.5 Concept E - Spherical Gears

During the literature review at the beginning of the project, a research paper was found that utilised spherical gears [39]. Concept E builds upon that project but instead of using four actuators, two to rotate and two to change the direction of rotation, this concept will of course only utilise two actuators, which in theory should be possible, by designing it like shown in figures 4.8 and 4.9. One actuator manipulates the elevation and one rotates both azimuth and polarisation. Both actuator gears should slide in the direction it does not manipulate.

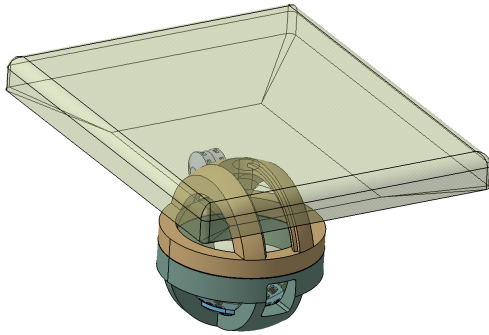


Figure 4.8: Concept E.

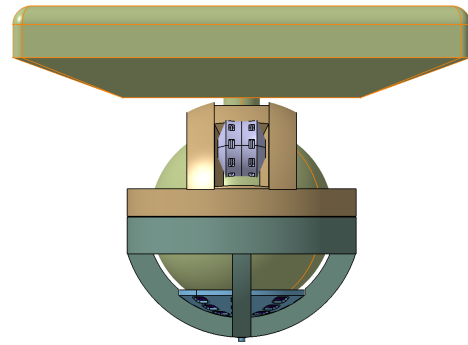


Figure 4.9: Concept E.

4.1.6 Concept F - Linear Gear Shifting

Concept F utilises a mechanism very similar to that of a gearbox in an automobile. It uses one rotating actuator for the rotation forwards and backwards and one linear actuator to shift gears. The different gears in the mechanism controls the different axis, one for elevation, one for azimuth and one for polarisation. This mechanism is easily implemented and the theory behind it is easily understandable.

4.1.7 Concept G - Differential

This concept is derived from the differential in a car, see figure 4.10. It works by having three bevel gears connected, two on the sides and one on the top. The two gears on the sides are actuated and manipulate the gear on top which is directly connected to the antenna. If the actuated gears rotate synchronously, elevation changes, and if they rotate oppositely, only polarisation changes. However, if only one of them are actuated, both elevation and polarisation change. Additionally, the worm gear driving one of the bevel gears is also connected to the azimuth axis. With this configuration, the four rotational inputs (two bi-directional motors) generate multiple, different, rotational outputs depending on combination. Table 4.1 shows the system of inputs and outputs in the actuated system, enabling full range of motion for the antenna. This concept works by executing specific rotations in a set sequence and can achieve all required angles. The full range of motion was validated by using a search algorithm to see if all output angles could be reached with the finite set of inputs, see appendix [A.1].

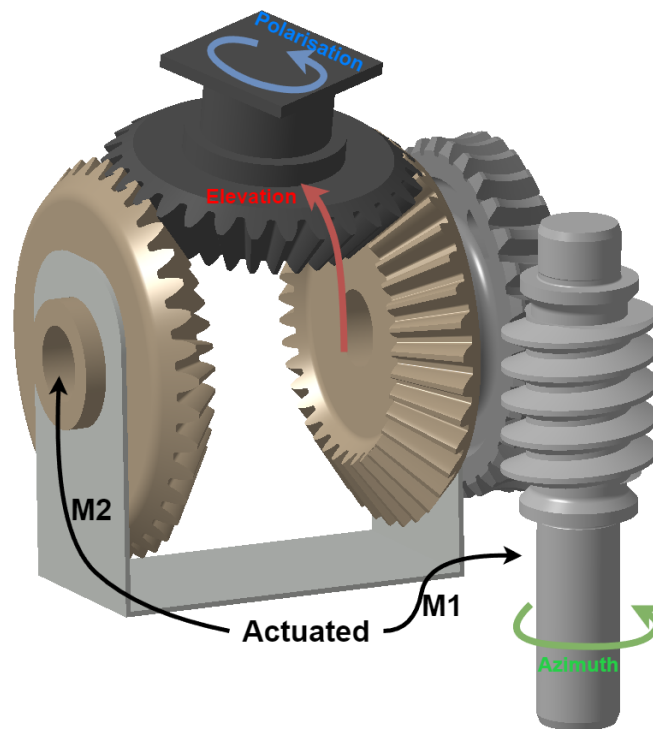


Figure 4.10: Differential mechanism of concept G.

Table 4.1: Logic of concept G:

CW = clock-wise, CCW = counter-clock-wise,
 ”-”, ”+” and ”0” indicates rotation in terms of the three axes of the antenna.

Actuation motor 1	Actuation motor 2	Output azimuth	Output elevation	Output polarisation
CW		-	+	+
CCW		+	-	-
	CW	0	+	-
	CCW	0	-	+
CW	CW	-	-	0
CCW	CCW	+	+	0
CW	CCW	-	0	+
CCW	CW	+	0	-

4.1.8 Concept H - Logic Gates

Concept H is more abstract than the other concepts, meaning it was never a concrete concept. It builds on the logic of Concept G on a theoretical level. The concept aims to use two rotating actuators as inputs, and with a mechanism consisting of mechanical logic gates, such as AND, NAND, OR, XOR, to retrieve unique rotational outputs. This means that the mechanism is very similar to a mechanical computer but where the inputs and outputs are rotating shafts instead. With the two rotating

actuators, 9 different states can be obtained by either not rotating, rotating clockwise, rotating counter-clockwise, individually or/and with both actuators. Figure 4.11 is an example of a mechanical XOR gate, showcasing the complexity of these type of mechanisms.

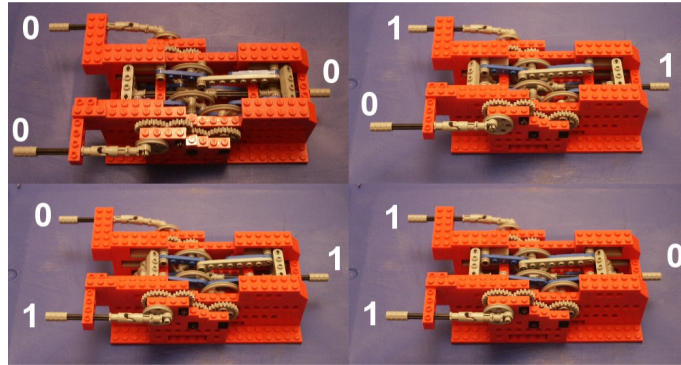


Figure 4.11: Example of a mechanical XOR-gate [6].

In theory it is possible to create a mechanism where the two input rotation shafts provide three unique output rotations, representing the actions in table 4.2.

Table 4.2: Logic of concept H: 1 = Clockwise rotation, -1 = Counter Clockwise rotation.

Actuator A	Actuator B	Output Pol	Output Azi	Output Ele
0	0	0	0	0
1	0	1	0	0
-1	0	-1	0	0
0	1	0	1	0
0	-1	0	-1	0
1	1	0	0	1
-1	-1	0	0	-1
1	-1	0	0	0
-1	1	0	0	0

4.2 Elimination Process

After all conceptual mechanisms were defined, the elimination process followed. In this phase, the different concepts were graded depending on how well they performed against each other based on criteria, using the concept-selection matrices described in the methods chapter (3.5). This section presents the results of the grading and then the resulting elimination of outperformed concepts.

4.3 Evaluation Criteria

Before the elimination process, the metrics in the specification sheet were revised to be proficient for the concept-elimination matrices. Most of the metrics in the specification could be directly translated into elimination criteria, with some of them being removed. For example, the metrics regarding terminal mounting type, terminal mounting time and anchoring system would not provide much difference between concepts, and were thus removed. There was also some newly acquired information, which led to the implementation of new criteria in the elimination-process:

- Azimuth sweeping - after a discussion with stakeholders at Satcube it was discovered that a precise angle for azimuth pointing is difficult to predict, due to the lack of precise azimuth sensors. Thus, enabling the product to do small adjustments in the azimuth axis after alignment became a newly implemented criteria.
- Auto reversal - during conceptualisation it became obvious that some concepts would be able to automatically point the antenna, but struggle in resetting its position after a use cycle. "Auto-reversal" is the reversal of the auto-pointing process, back to the initial antenna position.
- Power draw during pointing - a minor addition to the list of criteria, which could provide small differences between concepts.
- Components in mechanism - complexity of the design was not considered in the specification, hence the need for a criterion to promote simpler designs in concept evaluation.
- Mechanism Clearance - some concepts utilised mechanisms that require engaging and disengaging of components, and other friction-induced wear and tear. A criterion was added to assess the amount of clearance, if at all, was in the mechanisms.
- Kinematic chain length - in the literature review it was discovered that precision in a serial mechanism is highly related to the amount of joints, therefore concepts using shorter chains needed to be promoted.

4.3.1 Elimination matrix

The results from the elimination matrix were expected. Six of the presented concepts had been designed in detail, and deemed viable to fulfil the elimination criteria. Whereas Concept E and H did not make it through the elimination matrix, as a result of them being purely theoretical. These concepts did not have any conceptual designs at the time of the concept evaluation. Therefore, the decision was made to eliminate them due to this lack of information and focus was shifted to the other concepts instead (table 4.3).

Table 4.3: Elimination matrix.

Elimination matrix								
Solution alternative	Solves main problem	Fulfills all objectives	Realizable	Reasonable cost	Safe	Enough information	(+) Fulfills criteria (-) Do not fulfill criteria (?) More info needed	
							Comment	Decision
Concept A - Three actuators	+	-	+	+	+	+	Does not fulfill objective of having two actuators, however it will be kept to weigh the other concepts against	Kept
Concept B - Clutch	+	+	+	+	+	+	Meets all objectives	Kept
Concept C - Unidirectional Kardan	+	+	+	+	+	+	Meets all objectives	Kept
Concept D - Limit Bearing Kardan	+	+	+	+	+	+	Meets all objectives	Kept
Concept E - Saturnus	+	+	?	-	+	-	Questionable, not enough information present and will probably be very expensive to manufacture	Discarded
Concept F - Linear gear shifting	+	+	+	+	+	+	Meets all objectives	Kept
Concept G - Differential	+	+	+	+	+	+	Meets all objectives	Kept
Concept H - Logic Gates (Ratchet gears)	+	+	?	+	+	-	Questionable, not enough information present	Discarded

4.3.2 Pugh Matrix

Three iterations of Pugh matrices were applied to the remaining six concepts. Concepts A, G and B were randomly selected as datum concepts, these were used to grade against, one per iteration. After the three comparisons were made, see figures A.3, A.4 and A.5 in the appendix, the result expressed that some concepts were not as not as viable as the others. For example, concept C got negative values in all three comparisons meaning it would not be wise to continue its development. On the other hand, concept B which got positive values in every comparison and thus was chosen to continue developing. The results from the iterative Pugh matrices were that concepts B, D and G achieved satisfactory scores compared to the datum concepts in all three iterations. As a result those three were kept for the following Kesselring matrix and the final evaluation.

4.3.3 Kesselring Matrix

As previously described in the methods chapter, the criteria used in the Kesselring matrix received their relevance number using a weight matrix before the final elimination. The resulting matrix for this weighed grading is presented as a table in the appendix A.6. For example, azimuth precision was valued the highest and got a 1 at every comparison. This is because the signal strength of the antenna is radically affected by the azimuth precision. Similarly, azimuth sweeping was highly valued after a discussion with stakeholders at Satcube. On the other hand, it was

discovered that the precision for polarisation precision is not as important as the others.

After all three concepts were graded in the Kesselring, the result showed that all three were valid to continue with since they had very similar scores (table 4.4). Because time did not allow the development of all three concepts simultaneously, one concept had to be picked for the continued development. Because all three concepts were proven, handpicking any one of them would be acceptable. However, the final decision was based on the highest scoring concept, which turned out to be concept B - "Clutch". The general complexity of the concept, that is which of the concepts would be the easiest to develop with limited prototyping capabilities, also played a role in the final decision. The clutch concept was deemed better in this aspect as well, thus it was a great choice for further development. The concept had also begun its transition into the design phase whilst the other two were still in the earlier conceptualisation phase.

Table 4.4: Kesselring matrix.

Kesselring												
Criteria	Weight	Solutions										
		Ideal Concept values		B		D		G		B = Clutch	D = Limit Bearing Kardan	G = Differential
		v	t	v	t	v	t	v	t			
Weight	0.03	10	0.26	9	0.23	7	0.18	6	0.16			
Stowing volume	0.05	10	0.54	10	0.54	7	0.38	7	0.38			
Actuator amount	0.03	10	0.30	10	0.30	10	0.30	10	0.30			
Auto-pointer tripod manufacturing cost	0.02	10	0.24	7	0.17	7	0.17	8	0.19			
Azimuth range	0.04	10	0.43	10	0.43	8	0.35	9	0.39			
Elevation range	0.05	10	0.52	8	0.42	10	0.52	9	0.47			
Polarization range	0.06	10	0.61	10	0.61	9	0.55	8	0.48			
Azimuth precision	0.09	10	0.91	10	0.91	10	0.91	9	0.82			
Elevation precision	0.08	10	0.82	10	0.82	10	0.82	9	0.74			
Polarization precision	0.04	10	0.41	7	0.29	7	0.29	8	0.33			
Azimuth Sweeping	0.05	10	0.48	10	0.48	7	0.33	6	0.29			
Auto reversal	0.03	10	0.35	5	0.17	7	0.24	7	0.24			
Auto-pointing time in all axes	0.02	10	0.15	8	0.12	7	0.11	6	0.09			
Power draw during pointing	0.00	10	0.04	6	0.03	6	0.03	4	0.02			
Power draw once target position is achieved	0.08	10	0.78	10	0.78	9	0.70	10	0.78			
Operational ground inclination	0.01	10	0.13	6	0.08	8	0.10	8	0.10			
Operational temperature range	0.05	10	0.54	7	0.38	7	0.38	8	0.43			
Operational in sporadic wind gusts	0.05	10	0.48	6	0.29	7	0.33	8	0.38			
Operational in continuous wind speed	0.07	10	0.69	8	0.55	8	0.55	9	0.62			
Components in mechanism	0.04	10	0.41	7	0.29	7	0.29	7	0.29			
Deadzone Length	0.05	10	0.48	6	0.29	7	0.33	10	0.48			
Kinematic chain length (serial/parallel)	0.04	10	0.43	8	0.35	8	0.35	10	0.43			
Total ($T = \sum t_i$)				10		8.51		8.21				8.41
T / T_{max}				1		0.85		0.82				0.84
Rank				xx		1		3				2
Decision												

4.4 Final Prototype

Although arriving at one remaining concept, Concept B - Clutch (4.1.2), there was still plenty of development work left to be done. The concepts evaluated in the elimination process were conceptual mechanisms rather than finished products, thus most of the design choices were left out at that stage. The aim of the prototype was to create a minimal viable product to affirm the concept through validating the specification metrics set at the beginning. Out of the two categories of prototypes,

according to K. T. Ulrich and S. D. Eppinger, this thesis was inclined towards creating a "works-like" prototype, rather than a "looks-like" prototype, because the mechanism was far more valuable than aesthetics at an early development stage [9]. Additionally, a mechatronics system was built and integrated, with the aim to autonomously test the mechanism of the prototype together with a laser pointer as an indicator for the alignment.

4.4.1 Design process

Because of the many design choices in the detailed design of the prototype, an agile approach was adapted for this phase as well. Initially, the design intent was to create a CAD-design including the mechanism with some basic framework to give inspiration for following design iterations. The fixed design criteria inherent to the clutch concept (4.1.2) were listed at the outset of the design process. Figure 4.12 illustrates the design criteria required for the concept.

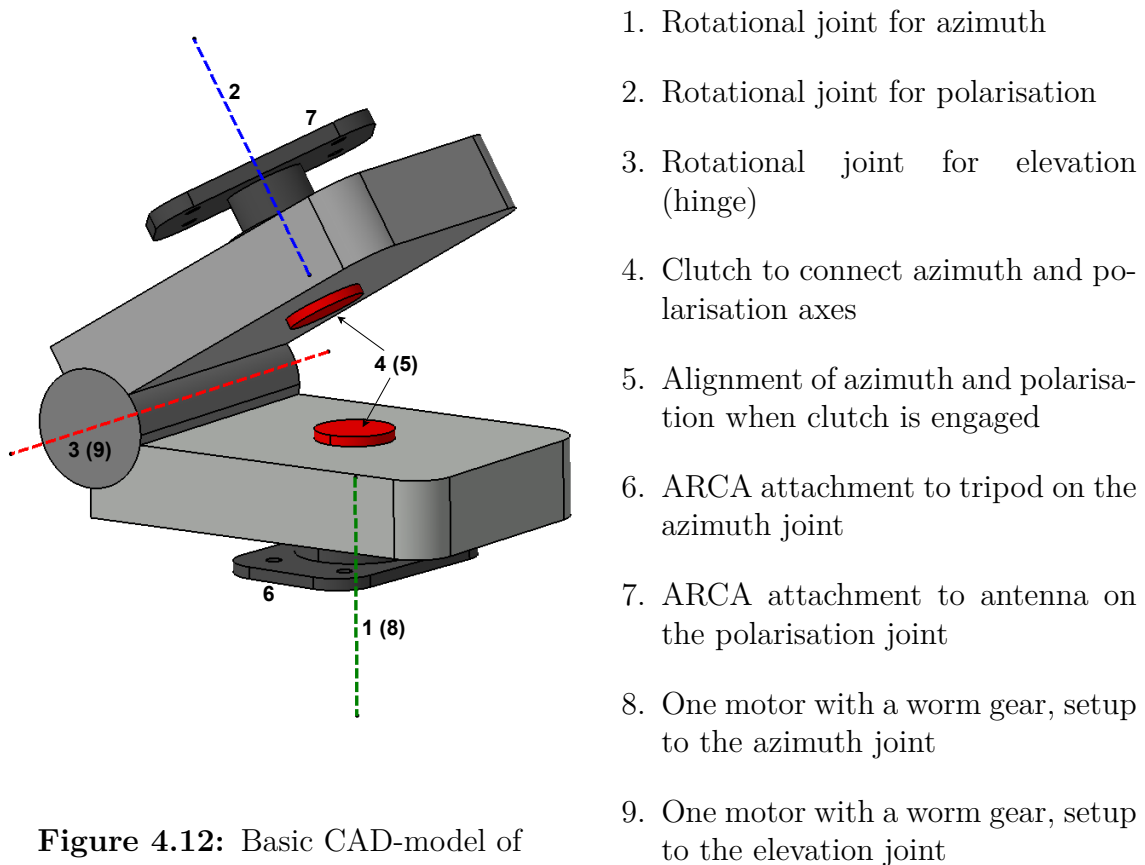


Figure 4.12: Basic CAD-model of concept B showcasing all design criteria.

1. Rotational joint for azimuth
2. Rotational joint for polarisation
3. Rotational joint for elevation (hinge)
4. Clutch to connect azimuth and polarisation axes
5. Alignment of azimuth and polarisation when clutch is engaged
6. ARCA attachment to tripod on the azimuth joint
7. ARCA attachment to antenna on the polarisation joint
8. One motor with a worm gear, setup to the azimuth joint
9. One motor with a worm gear, setup to the elevation joint

Two quite separate designs were proposed early in this stage, shown in figures 4.13 and 4.14. Both concept B.1 and B.2 comply to the design criteria, but the shape and motor placement composed the largest differences. Concept B.1 was an attempt to minimise the overall size of the product by encasing the two motors separately in two cylinders making a pincer-like shape. The elevation motor would be inside the

half which is elevated and actuate a worm wheel on the hinge, while the azimuth motor would stay horizontal and actuate a worm wheel on the vertical, clutch-axis.

Concept B.2 was more focused on keeping a simple, but yet compact shape. Both of the motors would be contained in the box, staying horizontal indefinitely, together with all electronic components. Actuating the hinge would elevate a plate holding the upper part of the clutch together with the antenna, thus keeping all mechatronic components enclosed within the box.

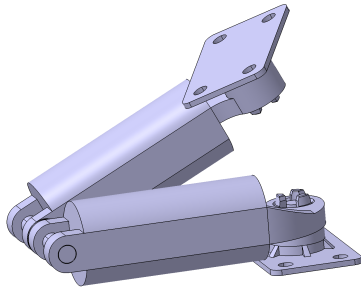


Figure 4.13: Concept B.1.

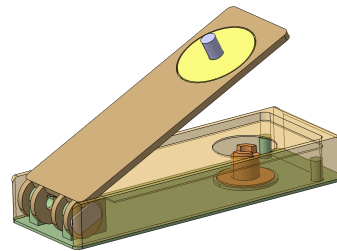


Figure 4.14: Concept B.2.

Both ideas had advantages and disadvantages and 3D-prints were made to further review them. The elevation of B.1 felt stiffer in up and down motion, but the hinge caused a twisting motion which slightly misaligned the clutch sometimes. B.2 had a sturdier hinge with more space and encapsulation for the mechatronic components, but the flat elevation arm showcased flexing behaviour which skewed the elevation angle. Also, placing both motors in a horizontal position in the lower compartment was advantageous to alleviate the mechatronic design and lowering the weight and inertia of the elevated part.

The conclusion was to keep both motors encased in a horizontal position, and rework the base such that there was more design space for the elevation arm. At this stage the motors predetermined to be used in the prototype was included in the design, along with worm gears and worm wheels, to iteratively get closer to a depiction of the final prototype. In concept B.3.1 (figure 4.15) the base was designed with a U-shape to provide more design space for the elevation arm in the hollowness. This design also created a convenient location for the electronic components within the walls of the elevation arm.

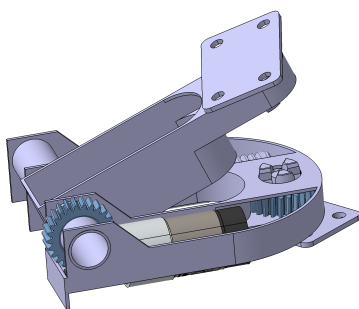


Figure 4.15: Concept B.3.1.

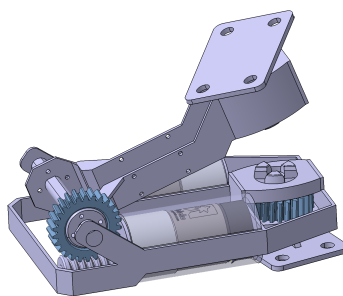


Figure 4.16: Concept B.3.2.

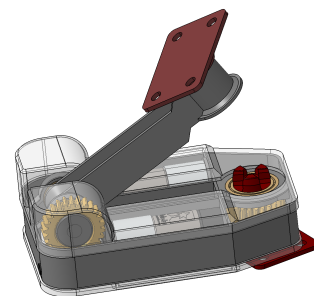


Figure 4.17: Concept B.3.3.

With a satisfactory shape of the prototype, more iterations were made (figures 4.16, 4.17). The goal of these iterations was to decrease the complexity of the frame, hence making the beginner manufacturing possible. If complex metalwork had been available, this amount of iterations might not have been necessary. Concept B.3.3 incorporated bearings for the joints as well as a first attempt at a plastic casing to advance the design towards water proofing. For each design iteration it became repeatedly more difficult to find obvious improvements, therefore a 3D-printed prototype of concept B.3.3 was created to alleviate the improvement process.



Figure 4.18: 3D-print of concept B.3.3.

Figure 4.18 depicts the first prototype with rotation in all axes, actuated from two axes. The intent of the rapid prototype was purely to find areas of improvements for the final design, thus it was fully printed using PLA instead of integrating actual, high-performance machine elements. The evaluation of the prototype was accelerated by implementing manually actuated shafts in place of the motors. In conclusion the prototype of concept B.3.3 successfully rotated in all axes, the clutch was reliably engaged and disengaged, the worm gears provided close to no backlash and it was non-backdrivable which was important to maintain alignment. Therefore the design was largely qualified for a final prototype with more rigidity and a mechatronic system.

4.4.2 Failure Modes and Effects Analysis (FMEA)

To systematically define possible problems of the prototyped version of concept B.3.3, a failure modes and effects analysis was conducted on the main mechanical aspects of the prototype. Using this method, actions to be implemented in the final

prototype were determined (see appendix A.2). Predominately, the failure modes of concept B.3.3 were related to misalignment of the clutch and tolerancing errors. Moving from 3D-printed components into metal components, it was crucial to find solutions for the possible failure modes at the detailed design phase. The FMEA showcased importance in accounting for tolerancing for the fixtures, for example, by designing larger holes in the front motor bracket, the azimuth motor could be adjusted slightly horizontally to align the worm gear with the worm wheel, before rigidly fastened.

4.4.3 Detailed Design of Final Prototype

Prototyping in metal required some design tweaks from the previous PLA prototype since additive manufacturing and 3D-Printing enables far more complex structures that are not possible to manufacture by amateurs in regular workshops. Most importantly, clever solutions for fixtures of the machine elements were required, without compromising the functionality demonstrated in the previous prototype. This meant that some parts had to be redesigned and some mechanisms had to be re-evaluated. For example, the frame of the auto-pointer had to be redesigned for water jet cutting, since the metal at hand was only 5mm.

Some designs were too hard to translate into metal and had to stay 3D-printed. The obvious part is the clutch, which is the most complex part of this system. Also, the elevation arm and the ARCA mounts were 3D-printed because of their high complexity. None of these parts would experience a high enough force to break them in the prototype, although a final product would require more structural integrity.

The parts of the prototype that were theorised to be under a heavier load were made out of metal. These parts were the frame, actuator mounts, and the mounts for the azimuth and elevation bearings. The parts that had to have high precision were bought, these were the gears. The prototype of concept B.3.3 (4.18) had 3D-printed gears, which quickly became the bottleneck of the system. This was due to the wear on the gears after just a few tests of the prototype, for example, the non-back drivable feature of the elevation became unreliable one day after the assembly, therefore the decision was made to buy gears for the final prototype.

4.4.4 Manufacturing

All manufacturing of the final prototype was done at Chalmers FUSE and consisted of 3D-printing and metal-work. The manufacturing was not done by professionals, this means that the final prototype could be done differently and/or better. However, the final prototype is used as a validation of the clutch mechanism and shall not be mistaken with the final product.

Table 4.5: Bill of Materials, final prototype.

Number	Component	Amount	Manufacturing	Function
1	Frame	1	Water Jet 5mm steel	Mounting bracket for every component
2	Actuator Mount	2	Metalwork	Mounting for actuators and Azimuth and Elevation Bearing holders
3	Azimuth Bearing	2	Purchased	Lower friction in rotational joint
4	Azimuth Bearing holders	2	Water Jet 5mm steel	Mounting brackets for Azimuth bearings, fixed to the azimuth actuator mount
5	Elevation Bearings	2	Purchased	Lower friction in rotational joint
6	Elevation Bearing Holders	2	Water Jet 10mm steel	Mounting brackets for elevation bearings, fixed to the elevation actuator mount and to the frame
7	Clutch	1	3D-Printed, PLA	Translate rotation from Azimuth to Polarisation
8	"ARCA" Mounts	2	3D-Printed, PLA	Mounting interface for the system
9	Microcontroller	1	Purchased	Controls the actuators to demonstrate functionality
10	Battery	1	Purchased	Power for microcontroller, motordriver and actuators
11	Worm gears	2	Purchased	Translating rotational force from actuator to Azimuth and Elevation axis
12	Worm Wheels	2	Purchased	Translating rotational force from actuator to Azimuth and Elevation axis
13	Actuators	2	Purchased	Used to demonstrate functionality
14	Motor driver	1	Purchased	Translate commands from microcontroller into inputs for actuators
15	Cables	X	Purchased	Used for signal transfer between electronic parts
16	Axle	1	3D-Printed	Translates rotation from wormwheel to elevation arm
17	Elevation arm	1	3D-Printed	Lifts antenna and disengages clutch
18	Clutch holder	1	3D-Printed	Mount for the Polarisation clutch, designed to self align
19	Bearing inserts	2	3D-Printed	Ensures that the elevation bearings are aligned
20	Screws	X	Purchased	To mount all parts together

The bill of materials (BOM) presents all the different parts that the final prototype consists of (table 4.5). It also describes their function and how they were manufactured. Figure 4.19 shows an exploded view of the final prototype with numbering of the parts, same as in the BOM.

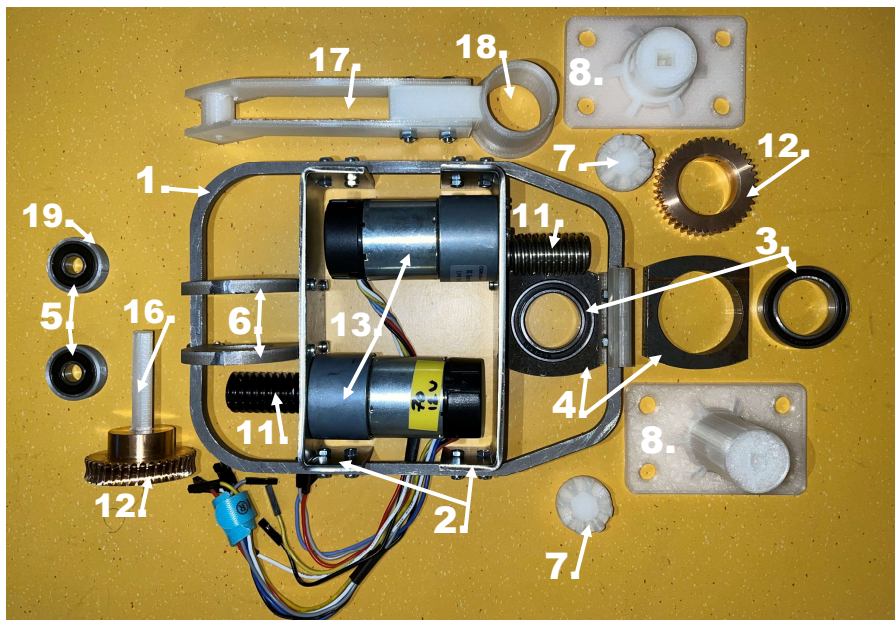


Figure 4.19: Exploded view of the final prototype with pointers according to the BOM.

The frame and both of the bearing mounts were cut out in a water jet because they had tolerances that would prove difficult to manufacture by hand. The frame and elevation bearing holders were cut out of 5mm steel sheets and the azimuth bearing holders were cut out of 10mm steel sheets.

The actuator mounts however, were created by hand from 3mm steel sheets since they could be manufactured in a way that accepted some tolerance errors. These mounts would also prove difficult to manufacture with the water jet would that have been tried. This is because it depends on a three dimensional design whereas the frame and bearing holders could be realised in two dimensions.

To compensate the need for good tolerances, the parts were designed and manufactured with tolerancing in consideration. All of the drilled holes for fixtures were slightly larger on one of the two components to be fastened. For example, the holes on the actuator mounts that are used to fix it to the frame are 4 mm, whereas the holes in the frame are 2.5 mm, enabling the components to be assembled despite minor misalignment and fixed in place with bolts, spacers, and nuts. The same applied when fixing the motors onto the actuator mounts, where the holes in the mounts were slightly larger than the motor shafts, enabling the motors to be fixed in place with optimal contact with the worm drive mechanism.

Some parts still had to be 3D-Printed because of their high complexity, they were the clutch, elevation arm and the ARCA mounts. The difference from the conceptualisation was that the final prototype was printed with higher resolution, slower and with more infill. This meant that the parts would have better tolerances and withstand higher pressures before yielding. Because of those aspects they have a better fit in a final design but not in a concept since they take a substantially more time to manufacture.

4.4.5 Mechatronics System

One of the aims of the prototype was to showcase its autonomous capabilities, therefore, a simple mechatronics system was implemented. Since the only purpose of the system was to test basic alignment and assess the range of motion in the prototype, a control system was deemed unnecessary. Additionally, the components were chosen based on what was accessible in the Satcube office, and what was deemed suitable for this prototype. For a mature product, the components should be further investigated and tailored for the product. The mechatronics system (figure 4.20) used in the prototype consisted of:

- Micro controller - Arduino UNO
- Motor driver - cytron shield mdd10
- Two brushed DC motors - CQR37D [40]
- 24 V NiMH battery

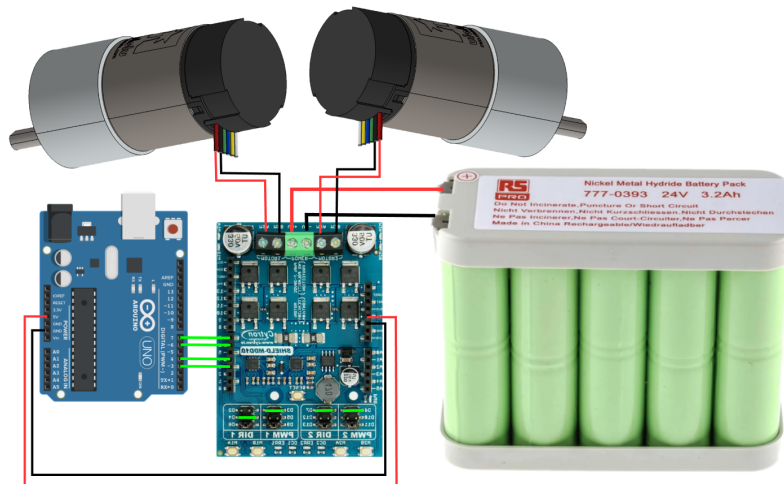


Figure 4.20: Mechatronics System.

The motors had integrated gearboxes with ratios of 50:1 and 210:1, resulting in output torque of 2.3, and 6.8 Nm. An assumption was made that the output torque provided a large safety factor for the weight of this prototype, and could safely be used for this evaluation. The motor with the higher gear ratio was mounted onto the elevation axis because it needed to lift the weight of the antenna, whereas the azimuth axis only needed to overcome the rotational inertia and friction in the prototype.

The programming was done in the Arduino programming language which is very intuitive, well-documented, and developed for the Arduino microcontrollers. The inputs were set and consisted of the sequence the antenna should be pointed. One negative aspect of the prototype was that the system could not know the exact angle of the polarisation, meaning that there existed no assurance that the clutch was aligned when engaging, which could have been solved with sensors. Additionally, this system had no method of detecting whether the clutch was engaged or disengaged, which had to be considered in the code so that it would not forcefully attempt to lower elevation when already at its minimum. The motor driver had integrated buttons that were soldered such that the motors could be actuated via manual inputs, used to safely re-engage the clutch.

4.4.6 Prototype Evaluation

The first step of the prototype evaluation was to identify if it accomplished the three elementary success criteria, stated in section 1.2:

- Align the antenna with any point in the visible hemisphere
- Maintain the alignment after the pointing process
- Mechatronic system to showcase its autonomous possibilities

The alignment toward any point in the visible hemisphere, or rather the range of motion of the auto-pointer, was validated by actuating the three axes. The testing was deemed to be safer by actuating the motors via the manual input buttons on the motor driver instead of an autonomous testing code. Resulting in unlimited rotation in the azimuth and the polarisation axes, however, for the polarisation axis, the wires became twisted around the top ARCA attachment if more than one full rotation was made. The elevation axis was also successfully actuated resulting in the antenna place-holder elevating from a horizontal starting position to a fully elevated position, showing no issues within the 90-degree range.

Figure 4.21 shows the auto-pointer in an elevated position, from a top view. Here, the bottom motor rotates the auto-pointer around the azimuth axis, relative to the wooden board below it. In figure 4.22 the auto-pointer is seen from the same viewpoint, but with the elevation arm horizontal. At the tip of the elevation arm, there is a cylinder guiding the top clutch onto the bottom clutch, resulting in azimuth and polarisation rotation when the clutch is engaged. The figurative antenna is removed in this picture, along with the bottom clutch, to be able to see the clutch alignment. The final figure, figure 4.23, is a side-view picture of the auto-pointer at an elevated position. The orange object, representing an antenna, is attached to the top clutch within the guiding cylinder. Additionally, in this final picture, the battery is disconnected, showcasing that the elevation is maintained without power being drawn.

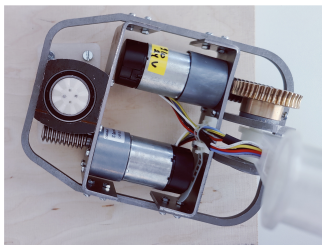


Figure 4.21: Azimuth actuation, top view.

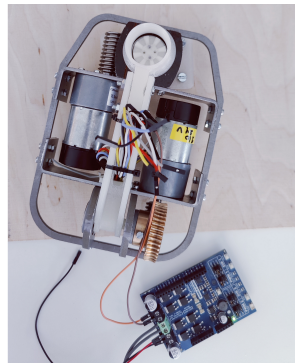


Figure 4.22: Polarisation actuation, top view.

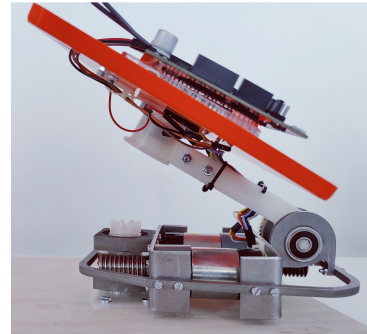


Figure 4.23: Elevation actuation, side view.

Maintaining the alignment was already validated for the concept with the earlier produced 3D print of concept B.3.3. However, with the implemented metallic worm drive mechanisms, the backlash was negligible. The only backlash in the joints was due to the shafts in the specific motors not being axially locked in the motors, leading to the worm gears being able to move slightly in the direction of the motor shafts, seen in figure 4.24. The worm-driven mechanisms were rigid and showcased that the concept was able to maintain alignment after the pointing process, whereas the prototype showcased the importance of rigid motor shafts needed to keep the worm gears in place. Additionally, since some of the parts along the elevated part

4. Results

were 3D-printed with PLA, such as the elevation arm, the flexibility enabled slight unpredictability in the elevated position.

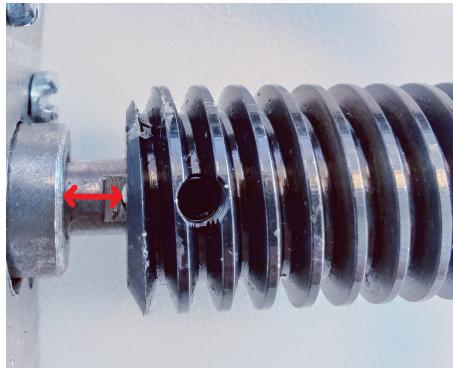


Figure 4.24: Backlash in the motor shafts.

As a result of being able to test the range of motion with the manual inputs, as well as a simple Arduino script, the mechatronic system was deemed successful for this particular prototype evaluation. This meant that the prototype was able to reach all possible points within its range using only the motors for actuation. However, the final prototype was by no means an autonomous auto-pointer for a UT. Although its "autonomous capabilities" were proven. For example, testing showcased that the elevation of the antenna was non-linear, due to the load torque shifting as the weight was displaced. Resulting in the non-feedback control system being inadequate for precision pointing.

Regarding the product specification, it was apparent that the prototype was not mature enough to be able to be tested in each metric. However, the metrics that were possible to test were measured and listed in table 4.6.

Table 4.6: Initial specification with validation.

Category	Metric No.	Metric	Units	Marginal Value	Ideal Value	Prototype validation
Physical properties	1.1	Weight	kg		<2	1,3
	1.2	Stowing volume	mm		<440x330x60	225x135x80
	1.3	Actuator amount	No.		<3	2
Product architecture	2.1	Terminal attachment type	type		ARCA	ARCA
	2.2	Terminal mounting time (onto attachment)	s		< 30	not tested
	2.3	Anchoring System	type		Tripod	ARCA
	2.4	Auto-pointer tripod manufacturing cost	\$		< 1000	~300
Operation performance	3.1	Azimuth range	° (degrees)	± 180	± 360	± 360
	3.2	Elevation range	° (degrees)	[10, 90]	[10, 170]	[0,90]
	3.3	Polarization range	° (degrees)		± 90	± 180
	3.4	Azimuth precision	° (degrees)	± 1	± 0.5	not tested
	3.5	Elevation precision	° (degrees)	± 1	± 0.5	not tested
	3.6	Polarization precision	° (degrees)	± 3	± 1	not tested
	3.7	Auto-pointing time in all axes	s		< 60	~30
	3.8	DC voltage	V		24	24
	3.9	Power draw once target position is achieved	W		0	0
Operation conditions	4.1	Operational ground inclination	° (degrees)		< 10	not tested
	4.2	Operational temperature range	° (celsius)		[-20, 55]	not tested
	4.3	Operational in sporadic wind gusts	m/s		< 20	not tested
	4.4	Operational in continuous wind speed	m/s		< 10	not tested

The physical properties were mostly within the ideal margins, with only the height of the prototype being too large. This is due to the excessive size of the worm wheel in the elevation joint, and the ideal margin was deemed achievable with a smaller gear. The weight of the prototype does not necessarily represent the weight of a final product, but it gives a good direction of what it could weigh. The size and the weight of 1.3 kg do not include the battery, which powered the prototype. The motors in an auto-pointer require only a fraction of the power drawn by the antenna in a typical UT, hence the choice and positioning of a battery, in a battery-driven UT with an auto-pointer, would preferably be made at a later stage in product integration.

The following category, product architecture, was more difficult to measure. Since the specification of the UT the auto-pointer would be integrated with, was undetermined, arbitrary ARCA attachments were designed for the antenna attachment and anchoring. Also, the same applied to the tripod, hence the terminal mounting time could not be tested. Regarding the cost, only the cost of the prototype was documented. Table 4.7 lists the costs of the components in the prototype assembly, totaling just below 300 USD when accounting for wiring and fixtures. Being well below the ideal value, it was deemed very achievable to produce the final product under 1000 USD.

Table 4.7: Approximate costs of the components in the prototype.

Component	Amount	Cost
DC-motor	2	\$22
Worm wheel	2	\$55
Worm gear	2	\$19
Elevation bearing	2	\$2
Azimuth bearing	2	\$4
Motor driver	1	\$26
Arduino UNO	1	\$26
3D-prints		~\$10
Metal		~\$6
Total		\$272

Operation performance was partly tested in the auto-pointer. As mentioned with the elementary success criteria of the prototype, it validated the full range of motion, subsequently validating the metrics on axis ranges. The precision was not possible to be tested because of the lack of a control system, meaning that the system was not able to point at specified coordinates, thus there was no point in measuring pointing accuracy. However, the auto-pointing time was successful, with a full actuation cycle within the three axes taking around 30 seconds. As well as the successful self-locking of the joints, which enabled the motors to draw no power when the antenna was elevated. Finally, the operation conditions were not possible to test with this prototype, because of the absence of a weather-proof casing.

The clutch mechanism of the prototype was also a focal point in the evaluation. It was not stated as one of the metrics to be tested, as it is concept-specific, however very important for the viability of the prototype. When the azimuth and polarisation axes were aligned, and the clutch engaged, the polarisation axis is perfectly actuated through the clutch. Disengaging the clutch did not seem to be a problem either, with the current clutch design. To keep the polarisation angle stationary when disengaged, high-friction tape was added to the clutch. This proved to be an adequate solution, but not optimal. It showcases that a friction-based solution is plausible, for example by implementing a rotary damper instead of the tape. The weakness of the clutch was in re-engaging it after a use cycle. If misaligned, the clutch did not fully engage and required some manual twisting of the antenna to fall into its fully engaged position.

The evaluation concluded that the initial hypothesis was confirmed - it is possible to achieve a full range of motion in the three axes using a design with only two actuators. The evaluation also brought great knowledge and ideas for further work on the concept, as it showed confirmation for some of the metrics, as well as showcased the possibility of reaching all requirements with some further development. This meant that the prototype was successful as a proof of concept, meaning that the concept itself was able to validate the requirements, although the prototype was lacking in some areas.

5

Discussion

Throughout the research and development of this project, several questions emerged regarding the scope under investigation. In this chapter, which will aim to address these questions and shed light on the various considerations that have shaped the results of this project. Specifically, it will discuss the relevance and justification of limiting the design to two actuators for the three axis rotation. It will also explore the potential impact of the product on the world and how it can contribute to address global challenges. Towards the end of the chapter it will also delve into the practical aspects of taking the proof of concept design towards a fully realised and marketable product. By thoroughly examining these topics, this discussion aim to provide a comprehensive understanding of the motivations, implications, and future prospects of the thesis.

5.1 Integrating Needs in a Subsystem

One of the challenges that arose early in the thesis, was the difficulty to implement existing customer needs studies for a subsystem product. A predefined user base already existed and needs were established for the existing terminal prior to this project. For example it was already known that the product was desired to be compact, light weight and portable, hence the subsystem was assumed to adopt to the same properties. However, developers of a subsystem must know when the implemented subsystem redefine the product to such a degree that new customer needs studies are required. For example, the trade-off presented in the needs analysis (3.2) - auto-pointing capabilities at the cost of a bulkier product, might require a more thorough analysis.

5.2 Auto-Pointers and Limited Actuator Amount

There is a lack of research on auto-pointers for portable satellite internet terminals. Innovating products in novel business areas with unique requirements is a challenge in itself, and without prior research it becomes even more difficult. The solution was to research other domains tackling similar alignment problems in multiple axes. Some examples of this are; thrust vectoring in aerospace, gimbal products for cameras and monitor stands. This research was crucial in the early conceptualisation

phase to find inspiration for the mechanisms that generated concepts.

In addition to the challenge of innovating a novel technology, the prefacing requirement of using two actuators in the product could possibly have limited innovation in the conceptualisation. An interesting thought would have been to further explore possibilities of designing with more actuators, or perhaps only one. Only by completing proper development processes of these alternative solutions could the final design be conclusively deemed an optimum solution. In the elimination phase of this project, an imaginary solution with three actuators, each mounted directly onto the three separate rotational axes, was used as a datum concept. However, without the proper research, there is not enough evidence that the conceived two-actuator design has strictly better performance than for example an auto-pointer with at least one actuator per joint.

5.3 Manufacturing and Precision

Since all of the manufacturing was done by hand in the workshops at Chalmers FUSE, it was also limited to the available tools. The main reason that the final prototype required a large number of alterations in the final design phase was because of this. Fortunately, as previously stated, some parts were able to be water cut by the staff in the workshop, however, ordering the remaining parts was not possible. Therefore they had to be manufactured by hand which lowered the precision by a substantial amount. Especially when drilling the holes in the frame, bearing holders, and actuator mounts. This was fortunately foreseen and all holes were made larger, which allowed the screws to penetrate even if the holes were not perfectly aligned.

However, the prototype still managed to prove the concept of utilising a clutch and fulfilled the aims that were set for the prototype in the beginning. The performance and precision of the prototype were not as important as if it would be a market-ready product. Had the CAD models been created with proper experience, with manufacturing in mind, the performance of the model would have been significantly improved. Additionally, if there was time for another iteration of the final prototype, all parts would be ordered from appropriate manufacturers, leading to all parts being manufactured in either steel, aluminium, or molded in plastic, and having superior tolerancing.

5.4 Mechatronics System

The functionality of the current mechatronics system and the programmed code is purely for demonstration purposes and therefore severely limits the abilities of the prototype. However, a more realistic and working mechatronics system should not be very difficult to implement, for a knowledgeable mechatronics engineer. The difference to the current state of function would be to connect and implement the encoders on the actuators as well as an IMU in the antenna. The encoders would enable the system to control the motors and the IMU would enable the system to

know the current angles of the antenna. Otherwise, the biggest difference will be the programming, these changes would be the most time-consuming. The recommendation would be to implement a PID controller, or equivalent, to reach the target angles.

5.5 Ethical Considerations

In general, the satellite internet industry is positively contributing to internet accessibility. The technology provides a different means of internet access without the otherwise required infrastructure, consequently aiding the expansion of internet access. All research done in this field will contribute to the fact that more people get internet access. Even though the thesis does not aim to increase internet accessibility a more user-friendly device would certainly do so. There are also situations where a manual setup of the device is not possible, an automated process is, therefore, necessary to be able to use the device at all.

Increasing the availability of satellite internet connectivity raises questions about the usages of it since it encompasses both positive and negative aspects. On one hand, satellite internet contributes to providing communication services during environmental catastrophes and humanitarian crises. To enable immediate response efforts in these areas, easy to use and reliable access to information and communication is crucial. It alleviates coordination among first responders, which subsequently aids in saving lives and mitigating the consequences of natural disasters. On the other hand, it is essential to acknowledge that the technology is also employed for purposes that may raise ethical concerns. In military operations and warfare, satellite internet enables real-time communication, surveillance and targeting capabilities. Thus, it raises complex moral questions when developing technology that might contribute to civilian harm, privacy violations and overall benefit violence in conflicted areas.

5.6 Further Work

The development of the auto-pointer represents a significant advancement in the field of autonomously aligning satellite internet terminals, which is becoming the natural method of alignment for user-based terminals. However, there are several areas that require further refinement for the case of this product's path towards commercialisation.

One direction of future work involves the exploration of solutions with fewer or more actuators. The current design was designed with the pre-specified amount of two actuators. This requirement is difficult to connect to a customer needs study, since it does not matter to a user how many actuators are in the product as long as it functions as intended, thus the thesis was more of a viability study for this type of solution. However, by further investigating a wider scope of solutions, not limited to two actuators it may be possible to find concepts with better performance. Conducting comparative studies with simulations and experiments on multiple concepts

would be necessary to find a true ideal configuration, regarding parameters such as precision, speed, power consumption among others.

In addition actuator exploration, the developed auto-pointer would benefit from research on clutch mechanisms. In the Prototype Evaluation (4.4.6), the weaknesses of the designed clutch became clear, for example misalignment when re-engaging the clutch. This indicated that the clutch needed either more notches, a better tapered shape to guide it into place or by solving the engagement through a control system. By outsourcing or developing a specifically tailored clutch for the product would further validate the product by enabling smooth and precise movement of the antenna. By researching the alternatives, for example friction, electromagnetic, or synchromesh clutches, the most suitable option could be found for this application. In addition, these clutches would need to be evaluated over a long use cycles to fully validate the final choice.

To progress from the prototype phase into a market ready product, extensive work in materials selection and final design considerations are essential. Conducting a detailed analysis of the structural properties of the individual components is crucial to ensure the product's durability, weight optimisation and cost-effectiveness. Additionally, the final design should be evaluated through thorough testing under various environmental conditions and operational conditions to validate all of the requirements (3.3).

Furthermore, adopting an agile approach for the development of the auto-pointer was a rewarding method which could be further investigated from an academic or industrial point of view. Agile methodologies, commonly employed in software development, can also successfully also be adapted to hardware projects. The iterative and adaptive approach it implies can ultimately lead to faster development cycles and more successful final products, which is why it is an appealing research subject for the near future.

6

Conclusion

To conclude this thesis, the purpose was to work together with Satcube AB and to research an alternative to the current method of aligning their antenna manually. It should automatically point the antenna in its three axes of rotation while utilising only two actuators. Since the product should be in line with Satcubes business idea it should also be highly portable, compact and lightweight. It was also to write a report that documents a well executed product development process which explains and describes all the methods practised throughout the project together with their results.

The report delves into the design and testing of the final prototype. However, it is important to note that, the purpose of the resulting prototype was to validate the concept of the clutch mechanism, further development is necessary before a final product can be presented. Nonetheless, based on the research conducted in this thesis, it can be confidently implied that the clutch mechanism is a viable solution for an auto-pointer in a portable UT. Provided that the clutch is further developed and a control system is integrated to ensure the concept is precise enough for real use. Additionally, the concept is likely lighter than a three-actuator solution, and probably more compact. However, these statements can not be proved simply through the research done in this thesis.

A portion of this thesis presented the potential benefits of agile prototyping in mechanical engineering. Incorporating agile principles into the development process has the potential to enhance overall efficiency and quality, especially in design-choices and prototyping. The use of agile prototyping in addition to a conceptualisation phase, enabled engagement with multiple concept designs and enabled more informed decisions. Visualising and experiencing different concepts aid in comprehension and ultimately lead to better outcomes.

This thesis serves as evidence that a well-executed product development process empowers engineers to innovate by leveraging existing mechanics in novel ways. Employing systematic and well-documented approaches ensures the selection of optimal product properties for the intended application. In this thesis, by embracing systematic methodologies and exploring innovative prototyping techniques, it was possible to overcome challenges and drive successful product development in complex domains.

Bibliography

- [1] Satcube, “Satcube KU,” 2023, [Online]. Available: <https://satcube.com/satcubeku> (accessed on: June 20, 2023).
- [2] P. S. Foresman, “Azimuth - pearson scott foresman archives,” [Image], 2007. [Online]. Available: <https://picryl.com/media/azimuth-psf-71f721>
- [3] VIGNERON and P. cb, “Radar-hauteur-en,” [Image], 2022. [Online]. Available: <https://commons.wikimedia.org/wiki/File:Radar-hauteur-en.svg>
- [4] Y. Ayalon, L. Damti, and D. Zarrouk, “Design and modelling of a minimally actuated serial robot,” *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 4899–4906, 2020.
- [5] H. Li, H. Yu, X. Tang, D. Wang, Q. Meng, Y. Chen, and Q. Du, “Design of a minimally actuated lower limb exoskeleton with mechanical joint coupling,” *Journal of Bionic Engineering*, vol. 19, no. 2, pp. 370–389, 2022.
- [6] A. Atzeni, “Lego logic gates and mechanical computing,” Website. [Online]. Available: <https://www.randomwraith.com/logic.html>
- [7] ESA (European Space Agency), “Types of orbits,” https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits, Accessed 2023.
- [8] G. Huang, *Design for X: Concurrent Engineering Imperatives*. Chapman & Hall, 1996.
- [9] K. T. Ulrich and S. D. Eppinger, *PRODUCT DESIGN AND DEVELOPMENT*, sixth edition ed. McGraw-Hill Education, 2015.
- [10] T. Gustavsson and P. Rönnlund, “Agile adoption at ericsson hardware product development,” in *InI 22nd NFF Nordic Academy of Management Conference (Aug 2013)*, 2013.
- [11] M. Joaquin, A. Alexander, B. Matthias, H. Jens, and P. Kristin, “Enhancing the additive manufacturing process for spare parts by applying agile hardware development principles,” in *2019 IEEE 10th international conference on mechanical and intelligent manufacturing technologies (ICMIMT)*. IEEE, 2019, pp. 109–116.

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- [12] Axess Networks, “Differences between bgan and vsat,” <https://axessnet.com/en/differences-between-bgan-and-vsat/>.
- [13] G. Heifner, “Introduction to vsat technology,” *Broadband Properties*, vol. 2, no. 4, pp. 24–29, 2004.
- [14] M. Gachev and P. Dankov, “Low profile tracking ground-station antenna arrays for satellite communications,” in *7th Nano-Satellite Symposium*, Varna, October 2016.
- [15] PR Newswire, “Soaring demand for global connectivity drives satcom terminal sales to us\$15 billion by 2030,” *PR Newswire US*, 02 2023. [Online]. Available: <https://www.prnewswire.com/news-releases/soaring-demand-for-global-connectivity-drives-satcom-terminal-sales-to-us15-billion-by-2030-301444444.html>
- [16] P. Amadesi, “The role of vsats and other small satellite terminals in the evolving telecommunications environment,” in *Proceedings of International Conference on Satellite Communications. ICSC’94*, vol. 1, 1994, pp. 59–66 vol.1.
- [17] Cobham SATCOM, “Explorer 6075lx system,” <https://sync.cobham.com/satcom/products/land-mobile/satcom/ka-band/explorer-6075lx-system-c-24/c-93/p-4294>.
- [18] Digisat International Inc., “inetvu ka-75v ka-band drive-away vehicle vsat antenna,” <https://www.digisat.org/inetvu-ka-75v-ka-band-drive-away-vehicle-vsantenna>.
- [19] Starwin Communication, “Product information - starwin communication,” <https://www.starwincom.com/productinfo/342892.html>, Accessed 2023.
- [20] M. Holmes, “Future investments in vsat: What you need to know,” *VIA Satellite*, vol. May/Jun, no. 1, pp. 3–3, 2017.
- [21] Satellite Evolution Group, “GVF 2018 Issue,” Online document, 2018. [Online]. Available: <https://www.satelliteevolutiongroup.com/magazines/GVF-20181/content/GVF-2018-Issue.pdf>
- [22] Bernardo Schneiderman, “SNG and Flyaway Antennas - Broadcast Applications,” Online webpage, 2021. [Online]. Available: <https://satellitemarkets.com/productsservices/sng-and-flyaway-antennas-broadcast-applications>
- [23] Y. Chen, Y. Chen, W. Luo, and G. Zhang, “Development and classification of worm drive,” in *The 14th IFToMMWorld Congress in Taiwan*, vol. 10, 2015.
- [24] Nguyen Duc Thang. (2023) Thang010146 YouTube Channel. YouTube. [Online]. Available: <https://www.youtube.com/@thang010146>
- [25] M. P. Mann, L. Damti, and D. Zarrouk, “Minimally actuated serial robot,” *arXiv preprint arXiv:1705.09890*, 2017. [Online]. Available: <https://arxiv.org/abs/1705.09890>

- [26] T. W. Yi-Wei, M. Michael, P. M. V, R. Jason, and K. Homayoon, "Design of a minimally actuated medical exoskeleton with mechanical swing-phase gait generation and sit-stand assistance," *Mechanical Engineering*, vol. 136, no. 9, pp. 18–21, 2014. [Online]. Available: <https://asmedigitalcollection.asme.org/memagazineselect/article/136/09/Special-Section/18/382509/Design-of-a-Minimally-Actuated-Medical>
- [27] M. Laffranchi, S. D'Angella, C. Vassallo, C. Piezzo, M. Canepa, S. De Giuseppe, M. Di Salvo, A. Succi, S. Cappa, G. Cerruti, S. Scarpetta, L. Cavallaro, N. Boccardo, M. D'Angelo, C. Marchese, J. A. Saglia, E. Guanziroli, G. Barresi, M. Semprini, and S. Traverso, "User-centered design and development of the modular twin lower limb exoskeleton," *Frontiers in Neurorobotics*, vol. 15, pp. 1–17, 2021.
- [28] P. Wilson, *Circuit Designer's Companion*, 4th ed. Elsevier, 2017, chapter 9 - General Product Design. [Online]. Available: <https://app.knovel.com/hotlink/toc/id:kpCDCE0022/circuit-designers-companion/circuit-designers-companion?kpromoter=federation>
- [29] R. Cooper and A. Sommer, "The agile–stage-gate hybrid model: A promising new approach and a new research opportunity," *Journal of Product Innovation Management*, vol. 33, pp. 1–3, 09 2016.
- [30] J. Drutchas and S. Eppinger, "Guidance on application of agile in combined hardware and software development projects," *Proceedings of the Design Society*, vol. 2, pp. 151–160, 2022.
- [31] B. Cliff, C. Kurt, C. Lisa, F. Philippa, L. Adrian, N. Raj, and R. Murray, "Agile 2 - the next iteration of agile," pp. 336–338, 2021, chapter 13.1 How Hardware and Software Differ (or Not).
- [32] B. Bender, *Requirements Engineering in the Context of IDE*. Cham: Springer International Publishing, 2020, pp. 587–614. [Online]. Available: https://doi.org/10.1007/978-3-030-19357-7_19
- [33] D. Göhlich, B. Bender, T.-A. Fay, and K. Gericke, "Product requirements specification process in product development," *Proceedings of the Design Society*, vol. 1, p. 2459–2470, 2021.
- [34] M. Fagnoli, E. Rovida, and R. Troisi, "The morphological matrix: Tool for the development of innovative design solutions," in *4th International Conference on Axiomatic design, ICAD*, June 2006, pp. 1–7.
- [35] D. Raudberget, "The decision process in set-based concurrent engineering - an industrial case study," in *DS 60: Proceedings of DESIGN 2010, the 11th International Design Conference*, D. Marjanovic, M. Storga, N. Pavkovic, and N. Bojcetic, Eds., Dubrovnik, Croatia, 2010, pp. 937–946.
- [36] S. Upcraft and R. Fletcher, "The rapid prototyping technologies," *Assembly Automation*, vol. 23, no. 4, pp. 318–330, Jan 2003. [Online]. Available: <https://doi.org/10.1108/01445150310698634>

- [37] J. Gardan, “Additive manufacturing technologies: state of the art and trends,” *Additive Manufacturing Handbook*, pp. 149–168, 2017.
- [38] S. G. Teng and S. M. Ho, “Failure mode and effects analysis,” *International Journal of Quality & Reliability Management*, vol. 13, no. 5, pp. 8–26, Jan 1996. [Online]. Available: <https://doi.org/10.1108/02656719610118151>
- [39] K. Abe, K. Tadakuma, and R. Tadakuma, “Abenics: Active ball joint mechanism with three-dof based on spherical gear meshings,” *IEEE Transactions on Robotics*, vol. 37, no. 5, pp. 1806–1825, 2021.
- [40] “DC Gearmotor SKU: CQR37D,” http://www.cqrobot.wiki/index.php/DC_Gearmotor_SKU:_CQR37D, accessed: June 15, 2023.

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Appendix 1

Table A.1: Gantt-schedule for the entirety of the project.

Tasks		Est. Working Hours		Est. Lead Time		MASTER THESIS DEVELOPMENT PLAN																											
		Research	Design			January	February	March	April	May	June																						
		Research	Design	Jan. 4	Jan. 5	Jan. 6	Jan. 7	Jan. 8	Jan. 9	Jan. 10	Jan. 11	Jan. 12	Jan. 13	Jan. 14	Jan. 15	Jan. 16	Jan. 17	Jan. 18	Jan. 19	Jan. 20	Jan. 21	Jan. 22	Jan. 23	Jan. 24	Jan. 25	Jan. 26	Jan. 27	Jan. 28	Jan. 29				
Milestone 1: Literature Studies		40	3 weeks																														
Research relevant literature																																	
Milestone 2: Initial conceptualization		15	1 week																														
Generate mechanical and electrical requirements																																	
Generate concept proposals		32	1 week																														
Define product drawings		48	3 weeks																														
Develop CAD models		120	3 weeks																														
Evaluate and selection of concepts to pursue		15	3 weeks																														
Milestone 3: Initial prototypes		48	4 weeks																														
Research (and purchase) relevant components		120	3 weeks																														
Develop mechanical components		80	3 weeks																														
Assemble electrical elements		22	1 week																														
Develop costs for testing																																	
Milestone 4: Initial prototype evaluation		15	1 week																														
Physical evaluation		48	2 weeks																														
Concept re-evaluation and/or optimization																																	
Milestone 5: Final prototype		60	3 weeks																														
Research (and purchase) relevant components		140	4 weeks																														
Develop mechanical construction		120	4 weeks																														
Assemble electrical elements		80	5 weeks																														
Develop test case for prototype																																	
Milestone 6: Final prototype evaluation and testing		32	3 weeks																														
Evaluate performance		15	2 weeks																														
Validate test criteria																																	
Milestone 7: Final presentation		48	3 weeks																														
Final presentation - Overview		15	2 weeks																														
Final presentation - Prototype		8	1 week																														
Final presentation - Report Showcase																																	
Milestone 8: Thesis report		300	20 weeks																														
Final report - Content		60	3 weeks																														
Final report - Quality assurance		4	1 week																														
Final report - Printing preparation		1250	22 weeks																														

- ★ Phase Milestones
- ★ Milestone 1: Compiled list of literature and knowledge of contents
- ★ Milestone 2: Clear concepts and CAD models thereof
- ★ Milestone 3: Working prototype(s) as proof of concept(s)
- ★ Milestone 4: Specification sheet of improvements and optimization
- ★ Milestone 5: Working final prototype
- ★ Milestone 6: Test validation sheet
- ★ Milestone 7: 30-45 min thesis presentation
- ★ Milestone 8: Thesis report

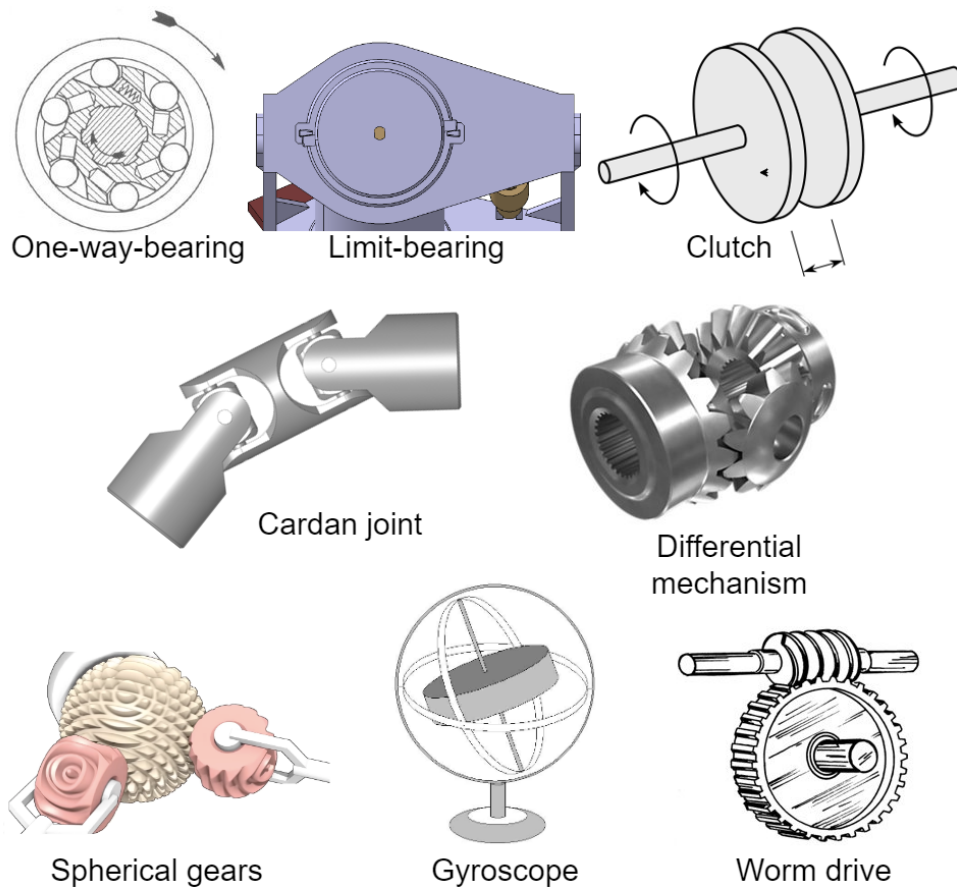


Figure A.1: The discovered mechanisms.

Question 1		Question 6		Question 10	
How often do you visit rural or remote areas		Importance of good connectivity		How much would a portable internet dish help	
Live there	12	1	0	1	4
Often	49	2	2	2	8
Sometimes	39	3	18	3	16
Rarely	0	4	31	4	27
Never	0	5	49	5	45
Question 2		Question 7		Question 11	
How often do you access the internet while in rural or remote areas?		How do you access the internet now		Most important features of the device	
Always	12	Mobile internet	73	Ease of use	42
Often	49	Fibre optics	15	Weight	14
Sometimes	39	Satellite internet	12	Size	29
Rarely	0	Other	0	Portability	47
Never	0			Reliability	57
				Performance	46
				Cost	23
Question 3		Question 8		Question 12	
Purpose of visit		Reason for internet		If available, likeliness to buy it	
Live there	19	Work	30	1	2
For work	12	Need for maps	15	2	4
Leisure	68	Browser	22	3	15
Other	1	Calls	7	4	30
		Games	3	5	49
		Social media	19		
		Other	4		
Question 4		Question 9		Question 13	
Quality of internet		What aspect of internet connection is important to you		Business model	
1	1	Reliability	47	One time purchase	53
2	5	Cost	8	Rental	36
3	35	Speed	45	Subscription	7
4	41	Other	0	None of the above	4
5	18				
Question 5		Question 14			
What is lacking in the internet there		Expected price			
Speed	42	4000 - 5000			
Latency	23	5000 - 6000	52		
Spotty access	33	6000 - 8000	16		
Other	2	> 8000	32		

IV **Figure A.2:** Previously conducted user survey for LEO-terminal.

1: What markets is the product suitable for?	2: Who are the potential users/customers/stakeholders?	3: What benefits can the product provide to the user?	4: What benefits can the product provide compared to existing solutions?	5: What aspects of the product are most important to the users/customers?	6: What will make the product easy to use?	7: What might be a suitable price and business model?
Organizations in northern Sweden	Organization managers in stationary camps	Publish videos/stories online	Connectivity in new areas	Reliability of connection***	Few buttons**	One time purchase*
People living in houses in remote areas	Journalists	Fast response time	Cheaper	Reliability of hardware	Powerbank integrated	1000 USD*
News stations	Firefighters	Access to internet everywhere**	Higher data limit (perhaps unlimited)	All-in-one unit**	Being able to start up with gloves on	Rent/hire*
The sami people and others like them	Broadcast companies	Live broadcasting	Easier to assemble	Vehicle mounting*	Not having that much to remember or learn	25K kr + approx. 500 kr per month
	Small businesses	Communication**	Cheaper	Easy and efficient setup***	Small and nimble design	
	Film makers	Portable due to battery	"Plug-and-play"	Portability*	Not having to do manual calibration	
	Raindeer herding	Live digital mapping (and other tools)	Smaller size	Low weight	Not having to rely on outside help	
	People living remotely	Only needing one device and subscription	Easier to protect from the weather	Easy to carry*	Connecting to it should be like regular wifi	
	Reporters that need to publish story quick	Easier to move between locations	Increased safety and access to help	Work at extreme temperatures	Not having to assemble	
	Tourists	Creating more business opportunities	Internet when there's no power	Power efficient	Router in unit and few other accessories	
		Reduces need for physical meetings, (travel)			Should be recyclable	

* indicates same/similar answer from several sources

Figure A.3: Previously conducted user interviews for LEO-terminal.

```
# Define the starting and goal positions as integers
# format: (azimuth, elevation, polarization)
start = (0, 0, 0)
goal = (5, 10, 3)

# Define the possible actions
actions = [
    ('M1CW', -1, 1, 1),
    ('M1CCW', 1, -1, -1),
    ('M2CW', 0, 1, -1),
    ('M2CCW', 0, -1, 1),
    ('M1CW_M2CW', -1, -1, 0),
    ('M1CCW_M2CCW', 1, 1, 0),
    ('M1CW_M2CCW', -1, 0, 1),
    ('M1CCW_M2CW', 1, 0, -1)
]

# Generate the graph on demand
def get_neighbors(node):
    neighbors = []
    for action in actions:
        new_node = tuple([max(min(x + y, 180), -180) for x, y in
            zip(node, action[1:])])
        if new_node == goal:
            return [(new_node, action)]
        elif action[1:] != node[-2:]:
            neighbors.append((new_node, action))
    return neighbors

# Find a path with consecutive actions of the same type using BFS
visited = set()
queue = [(start, [])]
while queue:
    node, path = queue.pop(0)
    if node in visited:
        continue
    visited.add(node)
    if node == goal:
        print("Actions taken from the starting position is:")
        print([(a[0],) for a in path])
        print("Node that has been reached:")
        print(node)
        break
    for neighbor, action in get_neighbors(node):
        queue.append((neighbor, path + [action]))
```

Listing A.1: BFS-search.

Table A.3: Pugh Matrix Concept A as Reference.

		Pugh Matrix							
Criteria	Weight	Solutions							
		Ref (A)	B	C	D	F	G		
Weight	5	-	1	0	0	0	0	0	0 A = Three actuator solution
Stowing volume	7	-	0	-1	-1	0	0	0	0 B = Clutch
Actuator amount	8	-	1	1	1	1	1	1	1 C = Unidirectional Kardan
Manufacturing cost	6	-	1	1	1	1	0	0	1 D = Limit Bearing Kardan
Azimuth range	3	-	0	0	0	0	0	0	0 F = Linear gear shifting
Elevation range	4	-	0	0	0	0	0	0	0 G = Differential
Polarization range	3	-	0	0	0	0	0	0	
Azimuth precision	8	-	0	0	0	0	0	0	
Elevation precision	8	-	0	0	0	0	0	0	
Polarization precision	6	-	-1	-1	0	0	0	0	
Azimuth Sweeping	6	-	0	-1	0	0	0	0	
Auto Reversal	4	-	0	-1	0	0	0	0	
Auto-pointing time in all axes	3	-	-1	-1	-1	-1	-1	-1	
Power draw during pointing	4	-	1	1	1	1	0	1	
Power draw once target position is achieved	10	-	0	0	0	0	0	0	
Operational ground inclination	2	-	0	0	0	0	0	0	
Operational temperature range	3	-	0	0	0	0	0	0	
Operational in sporadic wind gusts	4	-	0	0	0	0	0	0	
Operational in continuous wind speed	5	-	0	0	0	0	0	0	
Components in mechanism	5	-	0	-1	-1	-1	0	0	
Deadzone length	3	-	-1	-1	0	0	0	0	
Kinematic chain length (serial/parallel)	7	-	0	0	0	0	0	0	

Summary Table							
0	4	3	3	3	1	3	Total number 1
0	15	12	16	16	20	16	Total number 0
0	3	7	3	3	1	3	Total number -1
0	11	-16	3	3	5	4	Overall Weighted Sum

Table A.4: Pugh Matrix Concept B as Reference.

Criteria		Solutions							
		Weight	A	Ref (B)	C	D	F	G	
Weight	5	-1	-	0	0	0	0	0	A = Three actuator solution
Stowing volume	7	0	-	-1	-1	0	0	0	B = Clutch
Actuator amount	8	-1	-	0	0	0	0	0	C = Unidirectional Kardan
Manufacturing cost	6	-1	-	0	0	0	0	0	D = Limit Bearing Kardan
Azimuth range	3	0	-	0	0	0	0	0	F = Linear gear shifting
Elevation range	4	0	-	0	0	0	0	0	G = Differential
Polarization range	3	0	-	0	0	0	0	0	
Azimuth precision	8	0	-	0	0	0	0	0	
Elevation precision	8	0	-	0	0	0	0	0	
Polarization precision	6	1	-	0	0	0	0	0	
Azimuth Sweeping	6	0	-	-1	-1	0	0	-1	
Auto Reversal	4	0	-	-1	-1	0	0	0	
Auto-pointing time in all axes	3	1	-	0	0	0	0	-1	
Power draw during pointing	4	-1	-	0	0	0	0	0	
Power draw once target position is achieved	10	0	-	0	0	0	0	0	
Operational ground inclination	2	0	-	0	0	0	0	0	
Operational temperature range	3	0	-	0	0	0	0	0	
Operational in sporadic wind gusts	4	0	-	0	0	0	0	0	
Operational in continuous wind speed	5	0	-	0	0	0	0	0	
Components in mechanism	5	0	-	0	0	0	0	0	
Deadzone length	3	1	-	0	0	1	0	1	
Kinematic chain length (serial/parallel)	7	0	-	0	0	0	0	1	

Criteria	A	Ref (B)	C	D	F	G	Total
Weight	5	-	0	0	0	0	3
Stowing volume	7	-	-1	-1	0	0	15
Actuator amount	8	-	0	0	0	0	4
Manufacturing cost	6	-	0	0	0	0	0
Azimuth range	3	-	0	0	0	0	0
Elevation range	4	-	0	0	0	0	0
Polarization range	3	-	0	0	0	0	0
Azimuth precision	8	-	0	0	0	0	0
Elevation precision	8	-	0	0	0	0	0
Polarization precision	6	-	0	0	0	0	0
Azimuth Sweeping	6	-	-1	-1	0	0	-17
Auto Reversal	4	-	-1	-1	0	0	-10
Auto-pointing time in all axes	3	-	0	0	0	0	0
Power draw during pointing	4	-	0	0	0	0	0
Power draw once target position is achieved	10	-	0	0	0	0	0
Operational ground inclination	2	-	0	0	0	0	0
Operational temperature range	3	-	0	0	0	0	0
Operational in sporadic wind gusts	4	-	0	0	0	0	0
Operational in continuous wind speed	5	-	0	0	0	0	0
Components in mechanism	5	-	0	0	0	0	0
Deadzone length	3	-	0	0	1	0	1
Kinematic chain length (serial/parallel)	7	-	0	0	0	0	1
Total number	3	0	0	1	0	0	2
Total number	15	0	19	19	0	0	18
Total number	4	0	3	2	0	0	2
Total number	-11	0	-17	-10	0	0	-1
Overall Weighted Sum							

Table A.5: Pugh Matrix Concept G as Reference.

Pugh Matrix							
Criteria	Weight	Solutions					
		A	B	C	D	F	Ref (G)
Weight	5	0	0	0	0	0	- A = Three actuator solution
Stowing volume	7	0	0	-1	-1	0	- B = Clutch
Actuator amount	8	-1	0	0	0	0	- C = Unidirectional Kardan
Manufacturing cost	6	-1	0	0	0	0	- D = Limit Bearing Kardan
Azimuth range	3	0	0	0	0	0	- F = Linear gear shifting
Elevation range	4	0	0	0	0	0	- G = Differential
Polarization range	3	0	0	0	0	0	
Azimuth precision	8	0	0	0	0	0	
Elevation precision	8	0	0	0	0	0	
Polarization precision	6	0	0	-1	-1	0	
Azimuth Sweeping	6	1	1	0	0	0	
Auto Reversal	4	0	0	-1	1	0	
Auto-pointing time in all axes	3	1	1	1	1	0	
Power draw during pointing	4	-1	0	0	0	0	
Power draw once target position is achieved	10	0	0	0	0	0	
Operational ground inclination	2	0	0	0	0	0	
Operational temperature range	3	0	0	0	0	0	
Operational in sporadic wind gusts	4	0	0	0	0	0	
Operational in continuous wind speed	5	0	0	0	0	0	
Components in mechanism	5	1	1	1	1	0	
Deadzone length	3	0	-1	-1	0	0	
Kinematic chain length (serial/parallel)	7	0	-1	-1	-1	0	

Criteria	A	B	C	D	F	Ref (G)
Weight	3	3	2	3	0	0
Stowing volume	16	17	15	16	22	0
Actuator amount	3	2	5	3	0	0
Manufacturing cost	-4	4	-19	-6	0	0
Azimuth range						
Elevation range						
Polarization range						
Azimuth precision						
Elevation precision						
Polarization precision						
Azimuth Sweeping						
Auto Reversal						
Auto-pointing time in all axes						
Power draw during pointing						
Power draw once target position is achieved						
Operational ground inclination						
Operational temperature range						
Operational in sporadic wind gusts						
Operational in continuous wind speed						
Components in mechanism						
Deadzone length						
Kinematic chain length (serial/parallel)						
Total number	1	1	1	1	1	1
Total number	0	0	0	0	0	0
Total number	-1	-1	-1	-1	0	0
Overall Weighted Sum	0	0	0	0	0	0

Table A.6: Relative importance multiplier for the Kesseling Matrix.

Criteria	Determining relative importance of criteria used in selection of UT concept																						Sum	Rel. Importance	Rank	Weights	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22					
Weight	1	-	0	0	0	0	0	0	0	0.5	0	0.5	0.5	0	0	1	0.5	0.5	0.5	1	0.5	0.5	6	0.285714286	18	0.025974	0.025974
Stowing volume	2	1	-	0.5	1	0	0	0	0	0	0.5	0.5	1	1	1	0	1	1	1	1	0.5	0.5	12.5	0.595238095	6	0.054113	0.054113
Actuator amount	3	1	0.5	-	1	0	0	0	0	0.5	0.5	0	1	1	0	0.5	0	0	0	0.5	0	0.5	7	0.333333333	17	0.030303	0.030303
Auto pointer tripod manufacturing cost	4	1	0	0	-	0	0	0	0	0	0.5	0.5	0.5	1	0	0.5	0	0	0	0.5	0.5	0.5	5.5	0.261904762	19	0.02381	0.02381
Azimuth range	5	1	1	1	1	-	0.5	1	0	0	1	0.5	0	0	1	0	0	0	0	0.5	0	0.5	10	0.476190476	12	0.04329	0.04329
Elevation range	6	1	1	1	1	0.5	-	0.5	0	0	1	1	1	1	1	1	0	0	0	0.5	0	0.5	12	0.571428571	8	0.051948	0.051948
Polarization range	7	1	1	1	1	0	0.5	-	0	0	0	1	1	1	1	0	1	0.5	0.5	1	1	1	14	0.666666667	5	0.060606	0.060606
Azimuth precision	8	1	1	1	1	1	1	1	1	0	-	1	1	1	1	1	1	1	1	1	1	1	21	1	1	0.090909	0.090909
Elevation precision	9	1	1	1	1	1	1	1	1	0	-	1	1	1	1	1	1	0.5	0.5	1	1	1	19	0.904761905	2	0.082251	0.082251
Polarization precision	10	0.5	0.5	0.5	1	0	0	0	0	0	0	-	0	0.5	0.5	1	0	1	0.5	0.5	0.5	0.5	9.5	0.452380952	14	0.041126	0.041126
Azimuth Sweeping	11	1	0.5	0.5	0.5	0.5	0	0	0	0	0	1	-	1	1	0	1	0.5	0.5	0.5	0.5	0.5	11	0.523809524	9	0.047619	0.047619
Auto reversal	12	0.5	0	1	0.5	1	0	0	0	0	0.5	0	-	1	1	0	0	0	0	0	0	0	8	0.380952381	16	0.034632	0.034632
Power draw during pointing	13	0.5	0	0	0.5	1	0	0	0	0	0	0.5	0	-	1	0	0	0	0	0	0	0	3.5	0.166666667	20	0.015152	0.015152
Power draw once target position is achieved	14	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.047619048	22	0.004329	0.004329
Operational ground inclination	15	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	18	0.857142857	3	0.077922	0.077922
Operational temperature range	16	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	1	0	-	0	0	0	0	0	3	0.142857143	21	0.012987	0.012987
Operational in sporadic wind gusts	17	0.5	0	1	1	1	1	0.5	0	0.5	0.5	0.5	1	1	0	1	-	0	0	1	1	1	12.5	0.595238095	6	0.054113	0.054113
Operational in continuous wind speed	18	0.5	0	1	1	1	1	1	0.5	0	0.5	0.5	0.5	1	1	0	1	-	1	1	1	1	11	0.523809524	9	0.047619	0.047619
Components in mechanism	19	0.5	0	1	1	1	1	1	0.5	0	0.5	0.5	0.5	1	1	1	1	1	-	1	1	1	16	0.761904762	4	0.069264	0.069264
Deadzone Length	20	0	0	0.5	0.5	0.5	0.5	0	0	0	0.5	0.5	1	1	1	0	1	0	-	1	0.5	0.5	9.5	0.452380952	14	0.041126	0.041126
Kinematic chain length (serial/parallel)	21	0.5	0.5	1	0.5	1	1	0	0	0	0.5	0.5	1	1	1	0	1	0	0	-	0.5	0.5	11	0.523809524	9	0.047619	0.047619
	22	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0	0.5	0.5	1	1	1	0	1	0	0	0	0.5	0.5	10	0.476190476	12	0.04329	0.04329

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