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UiT NORGES ARKTISKE UNIVERSITET

Wire Gear for Small Rotary Actuator intended for Low Earth Orbit Applications.

Master of Science thesis 2018

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i. Abstract

In this master thesis, a small rotary actuator with wire driveline intendent for space solutions is developed and tested. The replication of the environment with focus on surface friction, surface roughness, and more dynamical related features are considered. Features like temperature, vibration, radiation and more are excluded to limit the size. This because the field of interest in this iteration is to see if a wire driveline can replace traditional gear transmissions for small rotary actuators in the future related to the simplest dynamical operational environment.

During this thesis a small rotary actuator was developed. The actuator was designed, so that angular rotational friction is represented in a feasible way, gear ratio accordingly to torque and power requirement and finally representative surface roughness and sizing as desired. In addition, the wire driveline was implemented in the most feasible configuration with a preload mechanism and a load cell to monitor tension in the wire related to slack in the wire.

Component and lifetime tests show that the actuator itself works satisfactory and represent the desired environment. The following half time result was obtained: The wire tension seems stable and minor degradation of the wire is noticed after 600.000 cycles of 0-180-0 deg.

As result by inspection, verification and validation of the tests and lifetime test, a wire driveline can replace traditional gear transmission. However, several aspects such as creep over time, knots and pretension is a major milestone to be completed in a more detailed iteration.

Overall it appears that wire drivelines could replace or complement traditional gear transmissions. However there exist issues that must be researched as mentioned.

Over all this thesis covers the following aspects in detail:

- Identification of design and system requirements.
- Identification of related stakeholders and associated risks.
- Verification and validation plan and methods.
- Ideation, concept and concept selection.
- Detailed design, production drawings and prototype.
- Verification of test and test results.
- Test report for lifetime test.
- Finalizing, risk iteration and conclusion.

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v. Abbreviations

APMA	-	Antenna Pointing mechanism assembly
CAD	-	Computer Aided Design
ECSS	-	European Cooperation for Space Standardizations
ESA	-	European Space Agency
HBM	-	Hottinger Baldwin Messtechnik GmbH
ID	-	Identification
KDA	-	Kongsberg Defence and Aerospace
Kgf	-	Kilogram-force
KSS	-	Kongsberg Space System
LEO	-	Low Earth Orbit
NASA	-	National Aeronautics and Space Administration
R&D	-	Research and development
SFK	-	Svenska Kullagerfabriken AB
SRA	-	Small Rotary Actuator
SSM	-	Small Satellite Mechanisms
TBC	-	To Be Complied
TBD	-	To Be Determined
UiT	-	The Arctic University of Norway
US	-	United States
USSR	-	Soviet Union
VOA	-	Vebjørn Orre Aarud
WG-SRA	-	Wire Gear for Small Rotary Actuator

1. Introduction

First of April 2018 an article about Elon Musk's project "Starlink" was posted on Norway's largest technology website. Starlink is a satellite constellation development program by Space X. Its aim is to develop low-cost, high-performance satellite bus and requisite customer ground transceivers to implement a new space-based internet communication system [1]. The article gives information about that the Starlink project, which is now accepted by the US government and give insight of Musk's plan to send up over 4000 satellites [2]. However, Musk is not the only interested audience in space-based internet. Greg Wyler founder of OneWeb aims accordingly *"This initial production of 900 satellites is planned for launch into low Earth orbit beginning in 2018, to deliver affordable Internet access globally."* Wyler aims to produce fifteen satellites a week and dramatically reduce the cost of satellites [3].

Accordingly, to Wyler the reason and need for a space-based internet are:

While the cities and suburbs of developed countries have broadband access, over 50% of the world, including rural America, Europe and Asia, remain without reliable high-speed connectivity. The impact in emerging markets is even greater, where many are without access even at their schools or community centers. Internet access is critical for digital government, health and education, and lack of access impairs financial growth when markets cannot develop, trade and become economically relevant to each other. This issue impacts everyone, and together we can solve it." [3].

This is the reason for my thesis. The low-cost satellite space race projects have needs for several thousands antenna pointing mechanisms and other mechanisms. Companies such as Space X and OneWeb may buy some features "off the shelf". This emphasizes that the market is ready for new technology and it's the right time to start looking into low-cost high-performance satellite parts for external companies such as KSS - a new market segment is opening. New workplace and economic growth may occur for KSS, Kongsberg City or even Norway. In 2016 I wrote a Bachelor of Science with the Small Satellite Mechanism (SSM) group, on the same topic – develop a low-cost, high-performance antenna pointing mechanism. This bachelor thesis is the foundation for this master thesis and includes background information, analysis and more related to low-cost, high-performance satellite mechanisms. The major change from the bachelor thesis and this master thesis is that the bachelor thesis was a multi discipline bachelor with electronics, mechanics and computer science. All information related to the bachelor degree can be found online by visiting http://hdl.handle.net/11250/2396923 or by contacting me directly by mail *vebjrn_aarud@live.no*.

In addition, this thesis is partly based on some classified information and test reports provided by Kongsberg Space Systems.

As briefly stated in the abstract, a wire geared small rotary actuator was developed during this thesis. First identification of stakeholder is done. I did this to ensure that I got a "big picture" of involving parts. This resulted in a good overlay of the presenter and audiences needs and desires and how important these needs and desires are related to the stakeholder and to the system. Example, because this is an early prototype, the customers – the buyer of the system is not seen as a major stakeholder. This because in order to have something to sell, the product itself has to be in place. Kongsberg Space System is the major stakeholder for this thesis and have high influence and interest.

Next up, a development plan and model were created to try fulfilling these stakeholder's desires. Since Space industry is a high standardized environment with rules, guidelines and regulation. A model with focus on systematic development, local iteration and documentation was selected. The model is based on the famous Vee-model but slightly modified to suit the project in the best matter. The result of selecting this model is this very systematic, detailed and well documented report. It is designed in a way so that every statement is connected and traceable – to ensure minimum risk and a very good prototype from the beginning.

As risk, regulation and uncertainty related to low Earth orbit is highly represented in the Space industry and for this thesis, a comprehensive risk analysis was made to gain a "big picture" on the probability and impact of "known" risks. A standard risk matrix and evaluation table is used to evaluate identified risk within their category. The project ended up with a total of 8.6 in total risk score meaning that it is unacceptable, and measures should be taken. This is of course normal but give an insight of how feasible the project is, just from the start before any engineering is done. At the end of this thesis the risk is revisited and redone to see if any risk has been mitigated.

The final part of the input before the design phase is an initial design, requirement generation and validation/verification method and plan. The initial design phase estimated what forces to be expected in the small rotary actuator. This was done partly to decide preselection of bearing and preload. The result was a semi optimized bearing configuration with its own load spectrum.

This bearing configuration generated several design requirements and with cooperation with stakeholders needs, a requirement table was made. By now all formalities, guidelines and more is set including verification and validation methods and design phase can begin.

After a long ideation phase, concepts were selected and rated. The concept where rated up to the most important requirement but also related to the most important stakeholder. This major process ended up with a very feasible concept which was detailed designed and produced, as shown in Figure 2 on the next page. Figure 1 shows the general process of my work in this thesis.

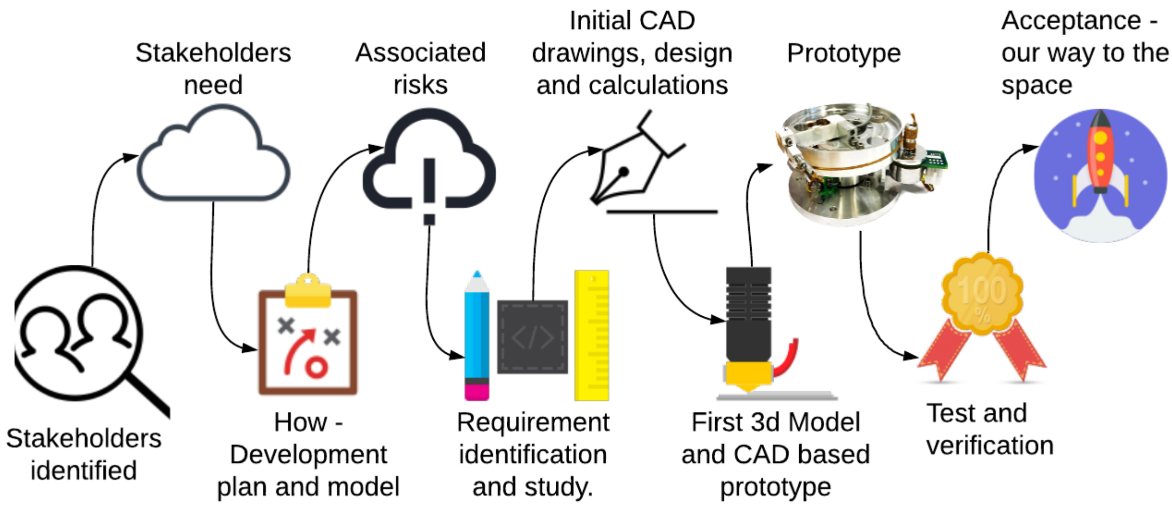

Figure 1: Process of my work.

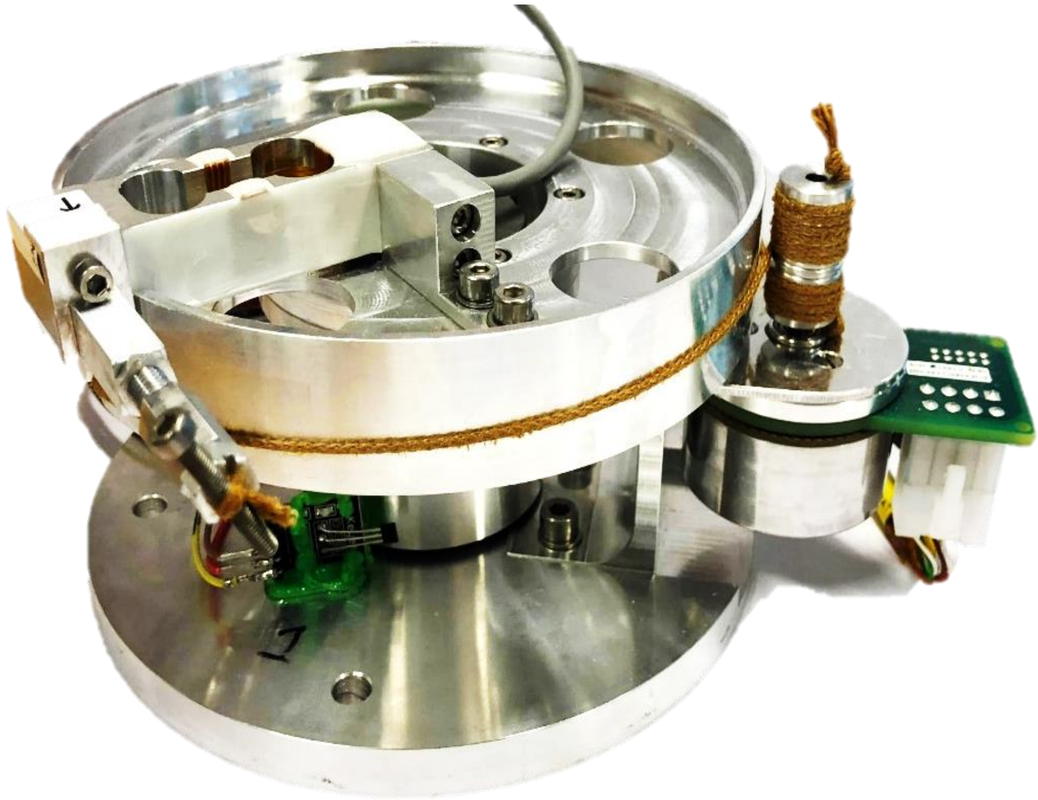

Figure 2: Final Prototype.

The total outcome and most important is the resulting lifetime test. The WG-SRA completed 1255860 cycles and kept its integrity. All in all, the glued knots to eliminate creep in connection points worked perfectly, the guide for electrical wire for the load cell eliminated wear on the load cell electrical wire, and the preload was above 2.0kgf during all cycles. The test was successful.

1.1. Thesis structure

The thesis consists of five parts and acts like standalone parts. Each part has its own abstract, introduction, list of figures and more. The first part, that you are now reading is called "Wire Gear for Small Rotary Actuator". It contains a short, but sharp and detailed version of the next four parts. Only the most important content, discussion and results are included. The reader is supposed to use the next four parts as a detailed reference for the given topic which may interest in depth. The second part, called Part A is the detailed introduction in the project. We define the boundaries in the project in more detail, project model and project tactics. In addition, we address risk, initial design, requirement and verification/validation methods that are wanted. In other words, Part A acts as the input of the Blackbox. The third part, called Part B is the design and construction in the project. Part B include a comprehensive concept study where several ideas are discussed, and concept is being made and selected, a large detailed design phase and several technical budgets. Part B ends with a prototype status and behave like the Blackbox – direct solutions based on the input in Part A. The forth part is Part C, called "hard testing and verification", is the part where we link the output of the Blackbox with the input. Part C contains a systematic verification prosses by tests addressed to the tests defined in Part A. Part C also include the main test of this thesis – a life time test of the wire geared small rotary actuator in vacuum. The last and final Part D is the finalizing and summary part for the whole project, it iterates the risk analysis, address experiences and ends this first iteration and master thesis.

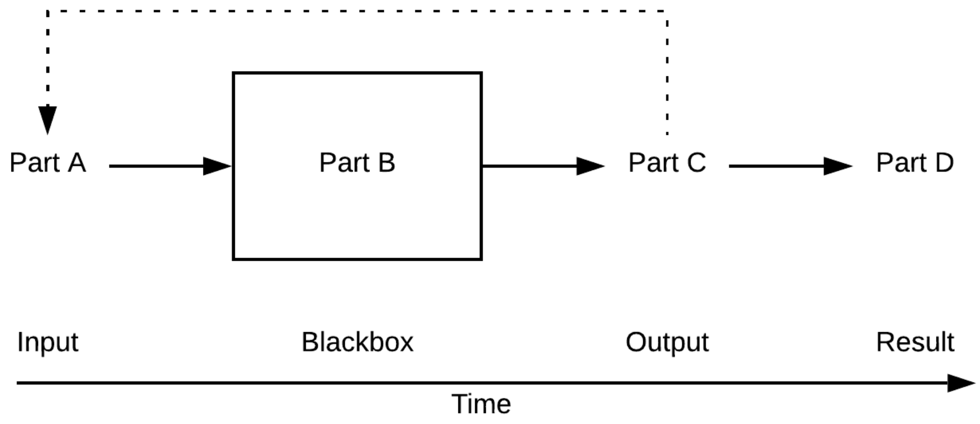

Figure 3: Thesis structure.

1.2. Governing APMA assembly from SSM

Figure 4 shows the Antenna pointing mechanism assembly developed by SSM where the azimuth and elevation assembly consist of one small rotary actuator each. In this master thesis the focus area is the azimuth actuator – which is an equal but larger actuator than the elevation one.

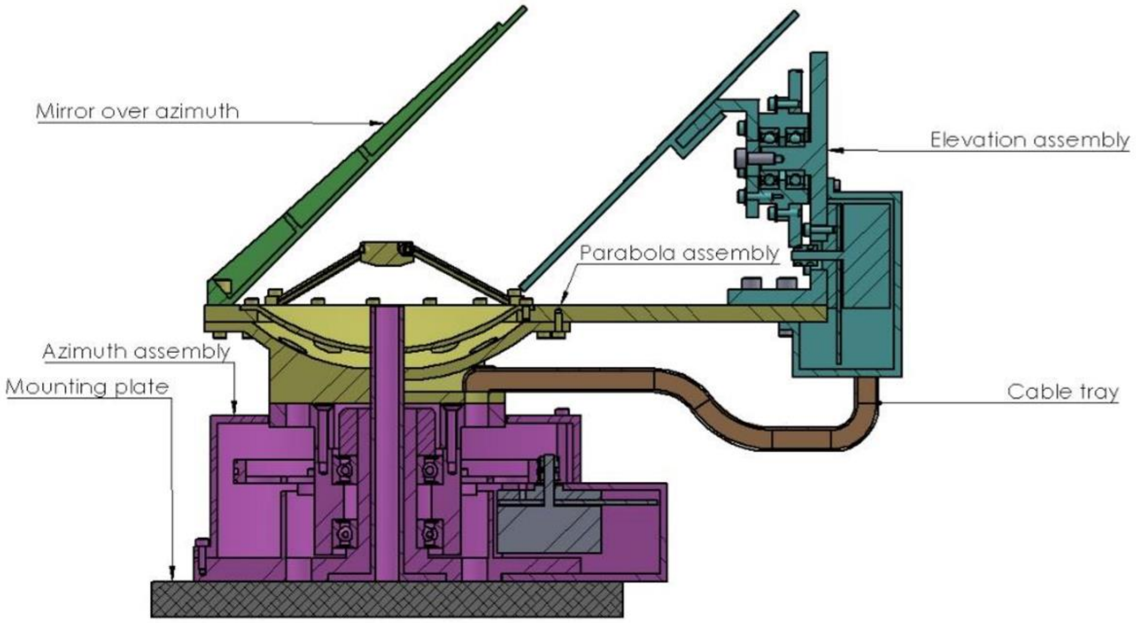

Figure 4: SSM APMA [4].

Figure 5 shows a detailed view for the azimuth assembly, note that it is driven by a large gear.

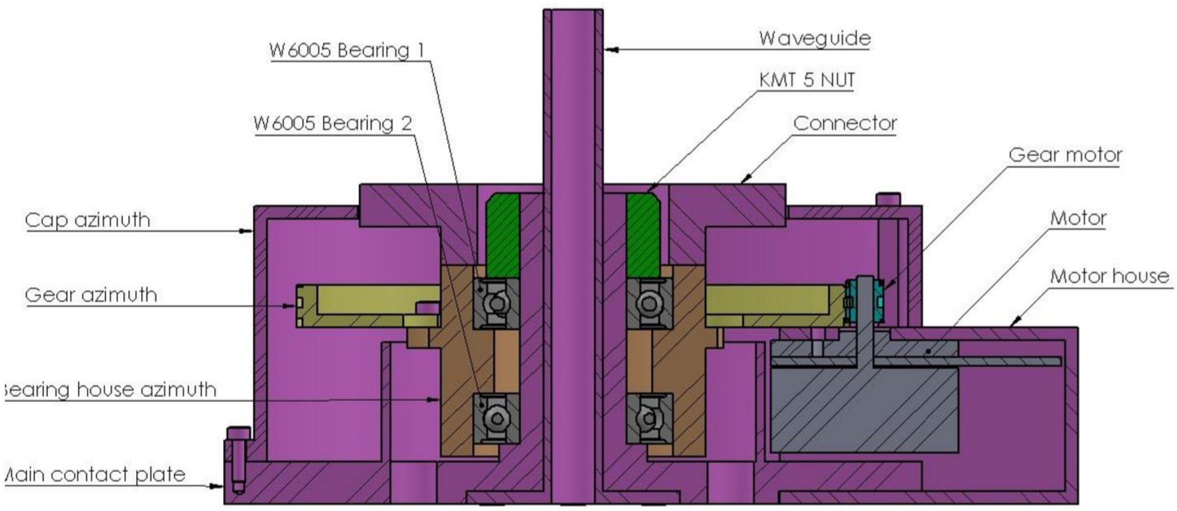

Figure 5: SSM Azimuth actuator/assembly [4].

The major issues with this actuator is relative high mass due to large stainless-steel gear and complications with backlash. In addition, this setup need more attention to lubrication, thermal effects and more.

2. Part A – Concept of Operation

2.1. Objective, Focus Areas & Results

The main goal for Part A is to create a foundation, an input or set of rules for the system. By system I mean all components included in the wire geared small rotary actuator. This is often done in a systematic way in system engineering. Stakeholders are identified, stakeholders need is discovered and the process of development regarding the stakeholder's need is started. As defined in the introduction Part A shall be the input of the Blackbox. This thesis will focus on developing the product with respect to function, the main area is preload in the wire, and friction between the wire and the pullies. The most important result from Part A, excluding the "handbook" of design rules is the bearing setup as shown in Figure 6. The whole design is dependent on the initial design. This because preload is highly linked to angular rotational friction, which affect motor torque, gear ratio and more.

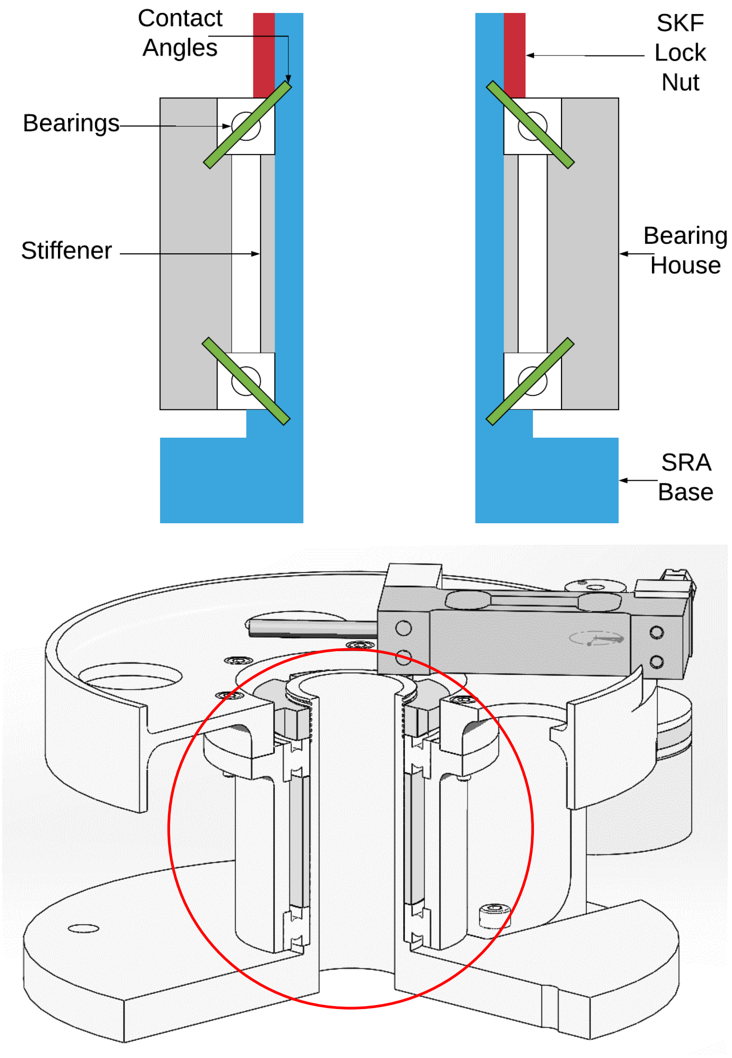

Figure 6: Bearing setup and implementation.

2.2. Kongsberg Space Systems & Stakeholders

Kongsberg Defence and Aerospace is one subdivision within the Kongsberg Group and one of Norway's supreme manufacture and developer of defence and aerospace related products and systems. KDA delivers systems for command and control, weapons guidance and surveillance, communication solutions, missiles and advanced composites and engineering products for aircraft and helicopter [5]. The subdivision inside KDA, Kongsberg Space Systems delivers a broad spectrum of systems and services related to space and maritime surveillance with customers in more than 40 countries. This included satellite components such as SADAM for Rosetta and KARMA-5 for the BepiColombo MTM spacecraft [6]. KSS is the thesis provider and seen as the major stakeholder of the thesis because of this. In addition, several other stakeholders are found and grouped in two categories. One called primary stakeholder. This is stakeholders that directly affect the system/project. The second is called secondary stakeholder. Secondary stakeholders indirectly affect the system/project. Figure 7 shows the identified stakeholders for this project and the reason related to the stakeholder.

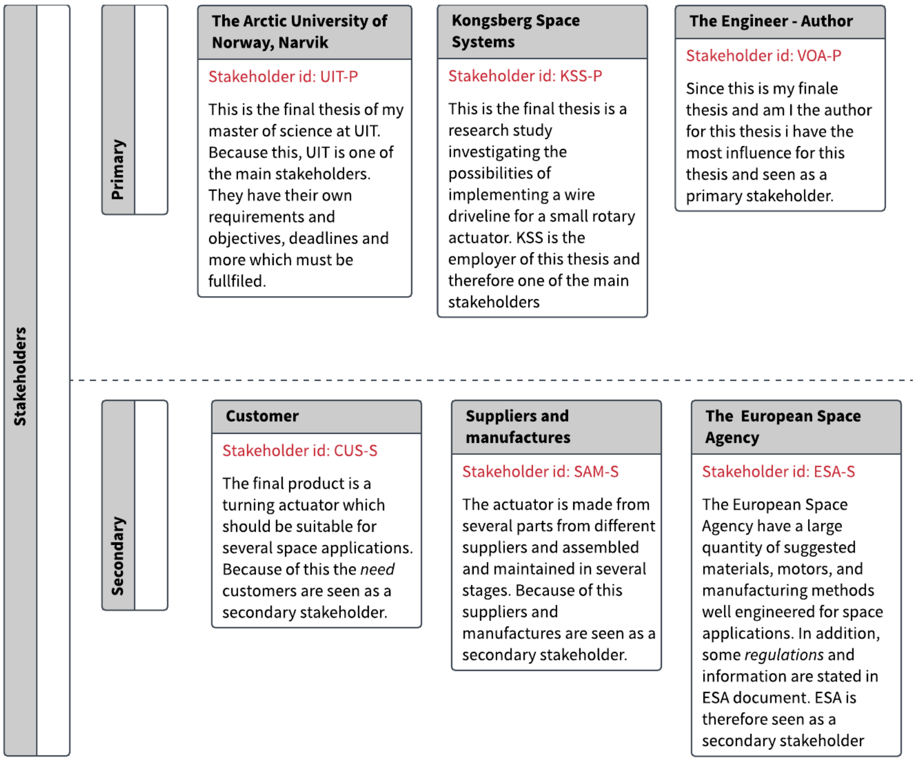

Figure 7: Stakeholders.

Figure 8 shows how these identified stakeholders relates to the project. The most noticeable stakeholders in this project are KSS, UIT, VOA and ESA with the following reasons. KSS is the employer of this task and described as a primary stakeholder because of its relation to the thesis. By interviews and meetings KSS empathize huge interest for redesigning the SRA. UIT is the second “authority” of this task and described as a primary stakeholder. UIT is not the technical stakeholder, moreover the formal one. UIT regulates formalities such as start/deadlines, supervisor, basic equipment and will grade this thesis. VOA is the author of this thesis and described as a primary stakeholder. VOA is a more personal stakeholder and the engineer executing this thesis. ESA is the third and a secondary stakeholder for this project. Since this is a master thesis in research and development of a new actuator in an early iteration of development its feasible to believe that ESA have close to no interest in this project at this point. However, ESA have loads of research and development that tends as regulations and guidelines for developing space solutions.

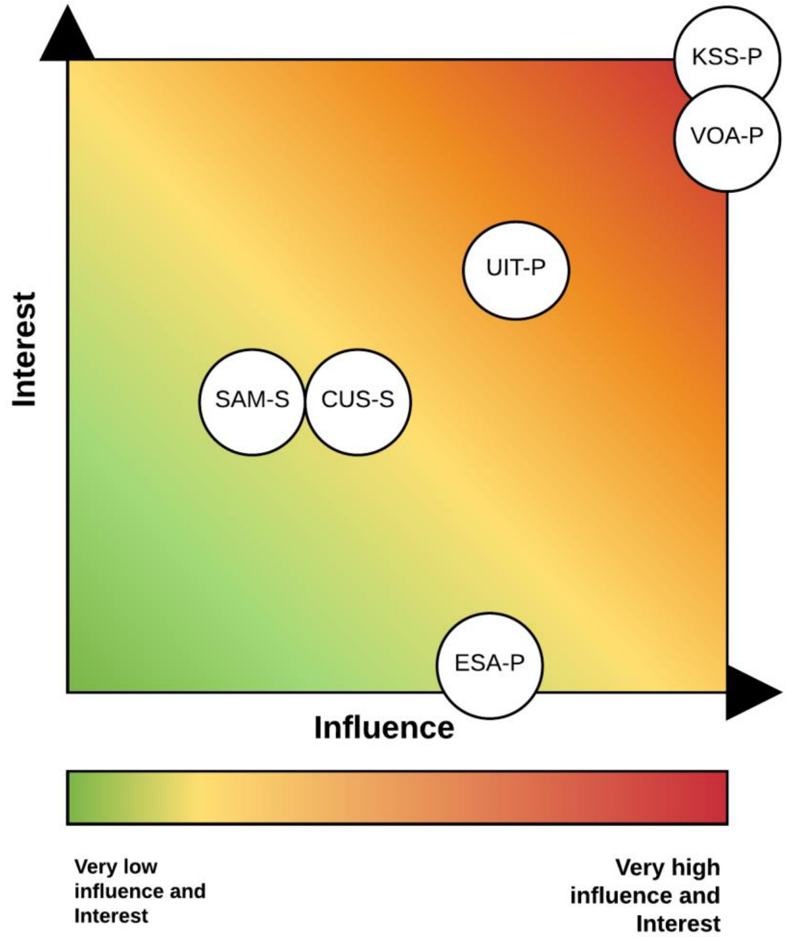

Figure 8: Influence and Interest chart.

2.3. Project Model & Tactics

The selected development strategy in this thesis is system engineering. System engineering is a technique which often are used in large and complex projects. It often uses a lot of "tools" to manage risk, requirement, relations and more. In this thesis, Alberto Sols book "Systems Engineering – Theory and practice" is used, and the selected model is self-made but highly dependent on the famous vee-model [7] and the framework in system engineering. Figure 9 shows the project model for this thesis.

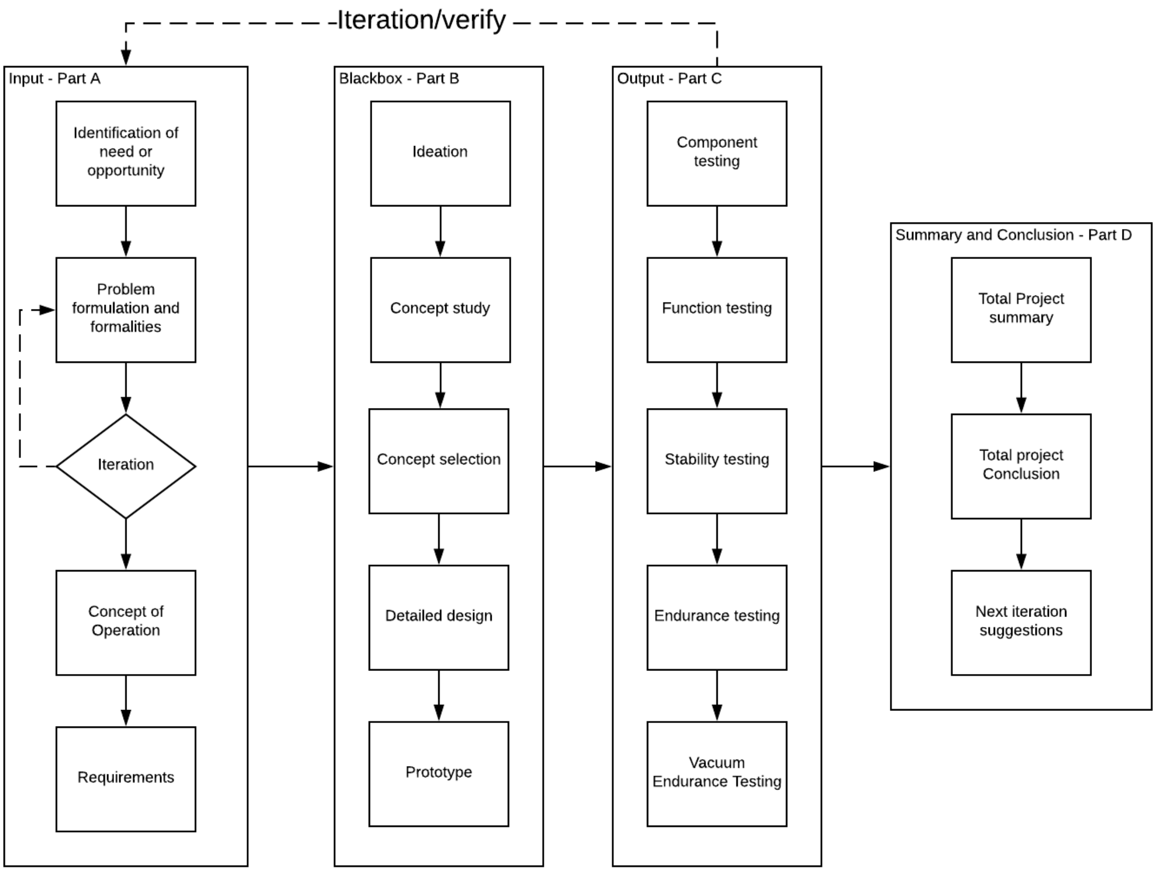

Figure 9: Project model.

The major advantages of this model because of the similarities to the vee-model is that. This model brakes down the system to help identify requirements, risk, challenges and more, even stakeholders. Its gives a very systematic and clear plan on what to do and how to do it – with great traceability. After the system is broken down, typically in Part A, Part B can start building up the system with the "new" given input. Ending with Part C to verify what happened inside the "Blackbox", Part B.

The major drawback of this model is that its take some time before a prototype is ready. The prototype can only first be being build when the detailed design is finished, and the system seems stable. However, the prototype is often very good from the start which is an important factor for this thesis related to testing.

Normally after Part C is done, a project status is given, in this case Part D and a new iteration can start or the project can be rejected for future iterations based on the results.

2.4. Initial Risk – Feasibility Study

Risk management is an important part of developing a new system or product. Especially space products that are going to be used for a long time without service.

Example, in 1957 the USSR launched the first successful satellite in orbit [8]. This started the "first" space race, who will be first on the moon? In 1969 Neil Armstrong was the first man on the Moon for USA [9]. I bring up this example because, a lot of products, features and money was invested during these years. Large risks where taken but USA was the first nation on the moon. After this space race, leading nations couldn't accept the risk associated to money, humans, or development any more. NASA also developed a program called Technology readiness level for new tech [10]. Mainly for tech to be accepted for "flight ready status". Because of this almost no "new" technology where made and the industry "died". Thus, a good risk management can early provide information on how feasible the product/system is and can give good strategies to handle upcoming or surprising cases, because of this the feasibility for new products may increase and R&D can evolve.

The following process shown in Figure 10 is used to found and evaluate risk in this thesis

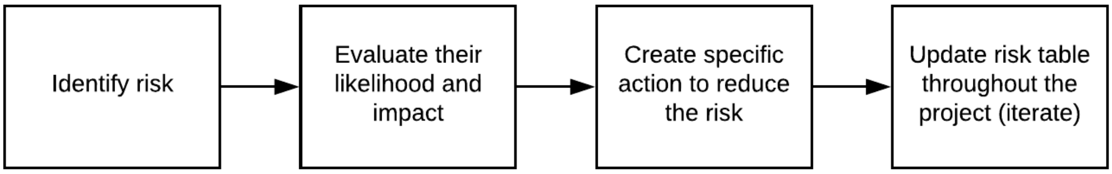

Figure 10: Risk Management process.

Table 1 shows the level of risk found in this thesis with its explanation. Figure 11 shows the results from the risk analysis preformed in this thesis with respect to likelihood and impact.

Table 1: Initial risk Explanations.

Risk level	Explanation
20-25	Unacceptable. Measures must be take to eliminate the risk
15-19	Unacceptable. Measure shall be take to eliminate the risk
8-14	Unacceptable. Measures should be take to eliminate
4-7	Acceptable. Measures should still be take to eliminate the risk
3	Acceptable. Measures may be take to eliminate the risk
0-2	Acceptable. No mitigation needed

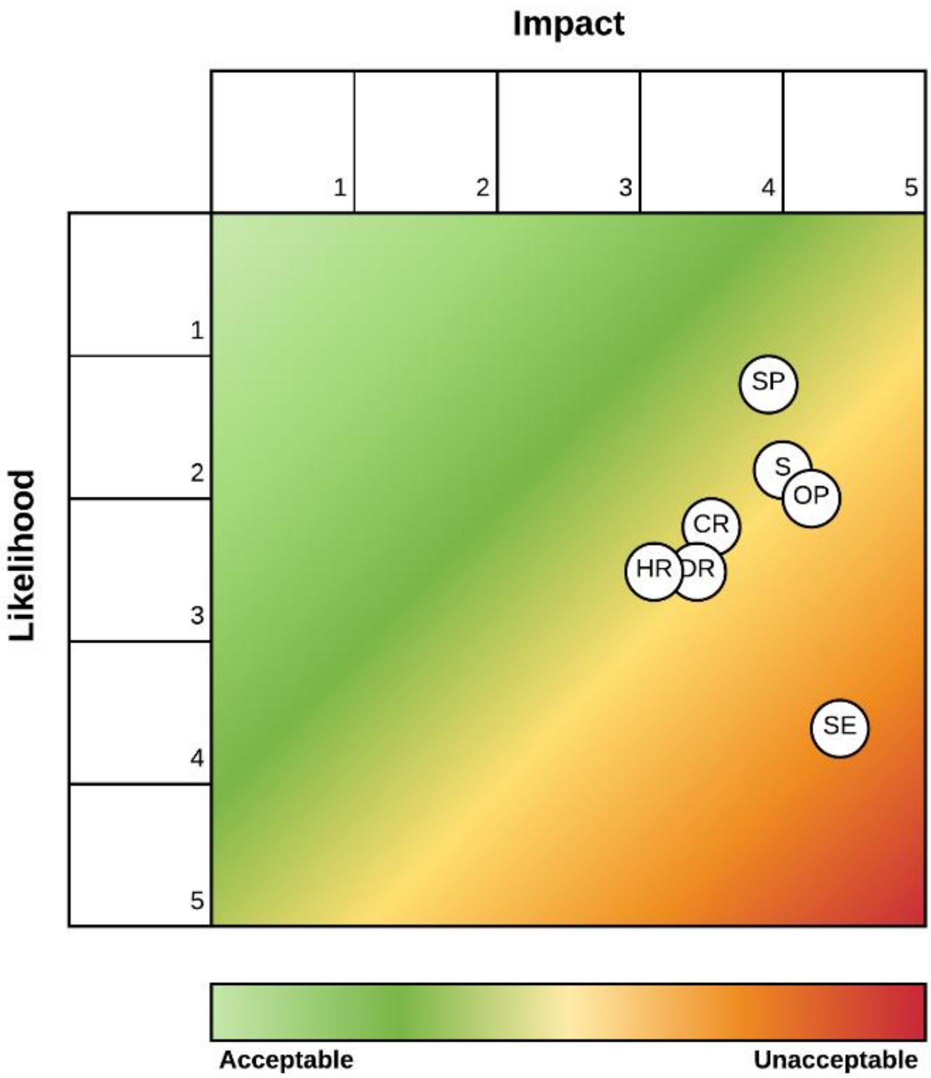

Figure 11: Impact – Likelihood.

Table 2 shows the result for the total risk related to both impact and likelihood.

Table 2: Initial Risk Results.

Risk:	**Disc code:**	**Risk value:**	**Note:**	**Mitigation:**
Space Environment	SE	16.4	Unacceptable and measures shall be taken to eliminate the risk	Follow mitigation plan, Part A Table 14.
Operation Risk	OP	8.8	Unacceptable and measures should be taken to eliminate the risk	Follow mitigation plan, Part A Table 15.
Human Resources	HR	6.3	Acceptable. Measures should be taken to eliminate the risk	Follow mitigation plan, Part A Table 20.
Development Risk	DR	8.3	Unacceptable and measures should be taken to eliminate the risk	Follow mitigation plan, Part A Table 19.
Cost Risk	CR	8.0	Unacceptable and measures should be taken to eliminate the risk	Follow mitigation plan, Part A Table 16.
Schedule Risk	S	7.3	Unacceptable and measures should be taken to eliminate the risk	Follow mitigation plan, Part A Table 17.
Safety Risk	SP	5.0	Acceptable. Measures should be taken to eliminate the risk	Follow mitigation plan, Part A Table 18.
Project risk (Not on figure)		8.6	Unacceptable and measures should be taken to eliminate the risk	

Thus, initial risk management indicates that the project status is unacceptable, and measures should be taken to eliminate the risk. Based on experience risk management in the first iteration is more to gather information than telling how feasible the project is. This result tells us that there are some challenges that should be dealt with. This is seen as feasible since very little engineering work have been executed. It's feasible to obtain an acceptable level of risk at the end of this thesis because of this.

See Part A appendix 7.2 Table 14, Table 15, Table 16, Table 17, Table 18, Table 19 and Table 20 for detailed information.

2.5. Initial Design, Requirements & Test methods

The WG-SRA in this thesis is one of several sub-systems in an APMA. To represent the rest of the system related to mass – to ensure that WG-SRA is designed to the right environment, an initial design study is performed. The main goal for this initial design study is to find estimated representative loads, related to the given environment. The following process shown in Figure 12 is used for this initial design study.

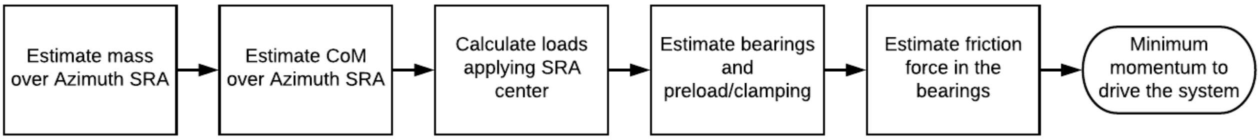

Figure 12: Initial design process.

Figure 13 shows a simple box model of the APMA where the SRA represent this thesis.

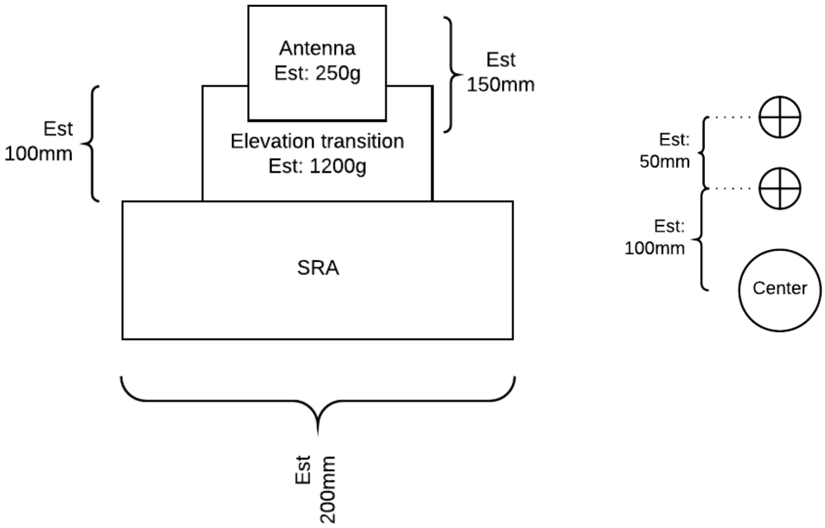

Figure 13: Box model of APMA.

By following simple calculations for center off mass

$$y = \frac{m_1 \cdot y_1 + m_2 \cdot y_2}{m_1 + m_2}$$

where m_1 is elevation transition mass and y_1 height to its center and m_2 is antenna mass and y_2 height to its center. We obtain that the load point representing the other sub-system is located 91.4mm offset from the WG-SRA center.

By using this estimation, forces on the center of the WG-SRA can be calculated. The WG-SRA operates in an environment where no g-force is applied to the system, the dominant acceleration in the system life-cycle is during launch, but not discussed in this thesis. However, the random vibration can replace the known g-force on Earth in LEO environment by applying Miles Equation [11]. Miles equation estimate the acceleration caused by random vibration of particles i.e the mass of the system.

$$G_{\text{rms}} = \sqrt{\frac{\pi}{2} f_{\text{n}} Q \left[ASD_{\text{input}} \right]} \qquad [1]$$

where f_{n} is the natural frequency of the system, Q is the amplification factor and ASD_{input} the input acceleration spectral density.

In discussion with KSS and based on experience with the SSM project the following specification for the values for Miles equation is: The worst case natural frequency of the system f_{n} is set to 140 Hertz, amplification factor Q to 10 and input acceleration spectral density to 1.5.

By applying these estimates with equation 1 we obtain the following acceleration for the system.

$$G_{\text{rms}} = 57.4 \text{ m/s}^2.$$

By using this acceleration, with Newton second law of motion, and in relation to 3σ maximum level in miles equation for design usage, the following forces for the system are:

$$\sum F = m3G_{\text{rms}} = 250 \text{ N},$$

where *m* is the total mass of the load point of 1450g. By applying the sum of forces in both horizontal and vertical axis the following resulting forces in the center of the WG-SRA are:

$$\sum F = F_{\text{x}} - F_2 = 0$$

$$F_2 = F_{\text{x}} = 250 \text{ N}.$$

By using the same principle,

$$F_1 = F_{\text{y}} = 250 \text{ N}.$$

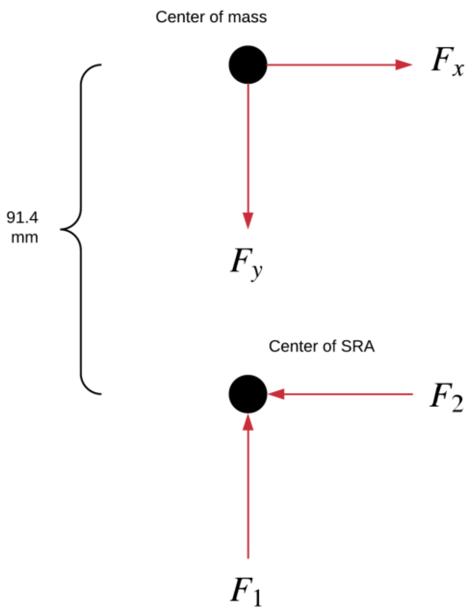

Figure 14: Force overview.

Now that the load spectra for the WG-SRA are estimated, bearing performance can be calculated to estimate angular friction in the system. A reference bearing from SKF with designation W63806 is selected. A scenario where two bearing is mounted with an offset of $\pm$ 20 mm is selected as reference as shown in Figure 15.

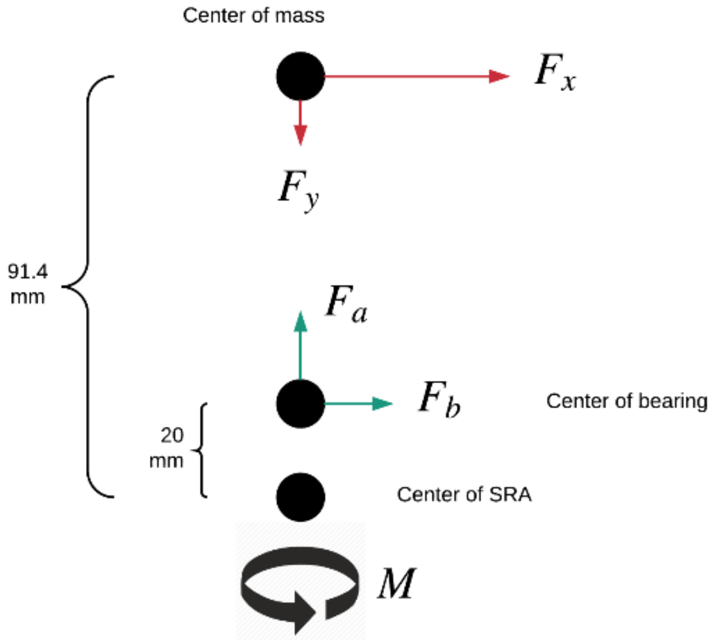

Figure 15: Bearing force overview.

By applying the same newton laws as for the reaction forces F_1 and F_2 in Figure 14. The following reaction forces in the bearing are found to $F_{\mathrm{a}} = 250$ N and $F_{\mathrm{b}} = 1140$ N.

By knowing the forces in the bearing, angular friction can be calculated. But first, the given preload for the load spectra must be estimated, then resulting contact, to obtain the right angular friction.

The reason for preload is to keep the bearings in position during random vibration in LEO, calculated with Miles equation. Especially the resulting force in radial direction since it is much greater than the axial force. If the bearing is not preloaded correctly the result can be huge pointing error due to low rigidity or too high torque friction. To estimate the preload with the selected reference bearing, maximum contact stress between the ball and the bearing house is calculated. The largest contact stress allowed is found by the maximum static load C_0 for the selected bearing.

By applying the following formula for contact stress [12]

$$P = \frac{1}{\pi}\left(\frac{\frac{6F}{N}{E^*}^2}{R^2}\right)^{\frac{1}{3}}, \tag{2}$$

where F is the load applied, E^* is the combined elastic modulus, R the radius of the ball and N number of balls in the bearing.

In this case we have the following resulting contact stress (Hertzian stress) at maximum static load on each ball:

$$P_{\max} = \frac{1}{\pi}\left(\frac{\frac{6C_0}{N}E^{*^2}}{R^2}\right)^{\frac{1}{3}} = 3648.8 \text{ MPa}.$$

Based on experience at Kongsberg Space Systems the suggested contact stress should be between 0.25−0.35 of the maximum contact stress, and suggested a factor of 0.35 to ensure correct lifetime. By applying this factor to equation 2 with $P = P_{\max}$ and solving for F, we obtain the given preload for the system. Note that the contact stress P is proportional with the force applied $F^{\frac{1}{3}}$.

$$3648.8 \cdot 0.35 = \frac{1}{\pi}\left(\frac{\frac{6F}{N}E^{*^2}}{R^2}\right)^{\frac{1}{3}}.$$

Thus preload $F = 132$ N with respect to all calculation above. This implies that the total forces acting in the bearing are $F_{\mathrm{a}} = 250$ N (axial) + 132 N preload = 382 N and $F_{\mathrm{b}} = 1140$ N.

By adding all these input to the bearing estimation calculation – selection of a more optimized bearing can be estimated. Table 3 shows the bearing optimizing. Note that for example preload adjust with different bearings.

Table 3: Bearing Optimizing.

Feature:	**Units**	**SKF 16006**	**SKF 61806**	**SKF 6006**	**SKF 61906**
Max Contact stress	MPa	3856.1	3806.5	4056.8	3924.3
Preload	Newton	334.4	131.9	337.65	207
SKF Total Frictional Moment	Newton millimeter	61.3	74.4	60.4	57.6
Bore	millimeter	30	30	30	30
Diameter	millimeter	55	42	55	47
Thickness	millimeter	9	7	13	9
Mass	Kilogram	0.089	0.025	0.12	0.049
Load Accepted	OK/Fail	OK	OK	OK	OK
Life Cycle Accepted	OK/Fail	OK	FAIL	OK	OK

All bearings except SKF 61806 is suitable for the WG-SRA, however SKF 61906 has the lowest mass and lowest total frictional moment of the passing bearings. SKF 61906 is therefore selected as the bearing for this WG-SRA. In addition, Kongsberg Space System want to multiply this angular friction with 3 to adjust for worst case and uncertainties. Thus, total torque to overcome friction for this system is therefore 172.8 Newton millimeters – 0.1728 Newton meter for each bearing.

This initial design study generated the following design requirements

- The driveline must overcome the friction in the SRA estimated to 0.1728 Nm for each bearing.
- The SRA must use SKF 61906 ball bearings.
- The SKF 61906 ball bearings must be axially preloaded with 207 Newtons.
- The mass over azimuth SRA most not be higher than 1.450 kg.
- The center of mass must be concentric with SRA center of mass.

In addition to these generated requirements, a process of finding other requirements is applied and shown in Figure 16.

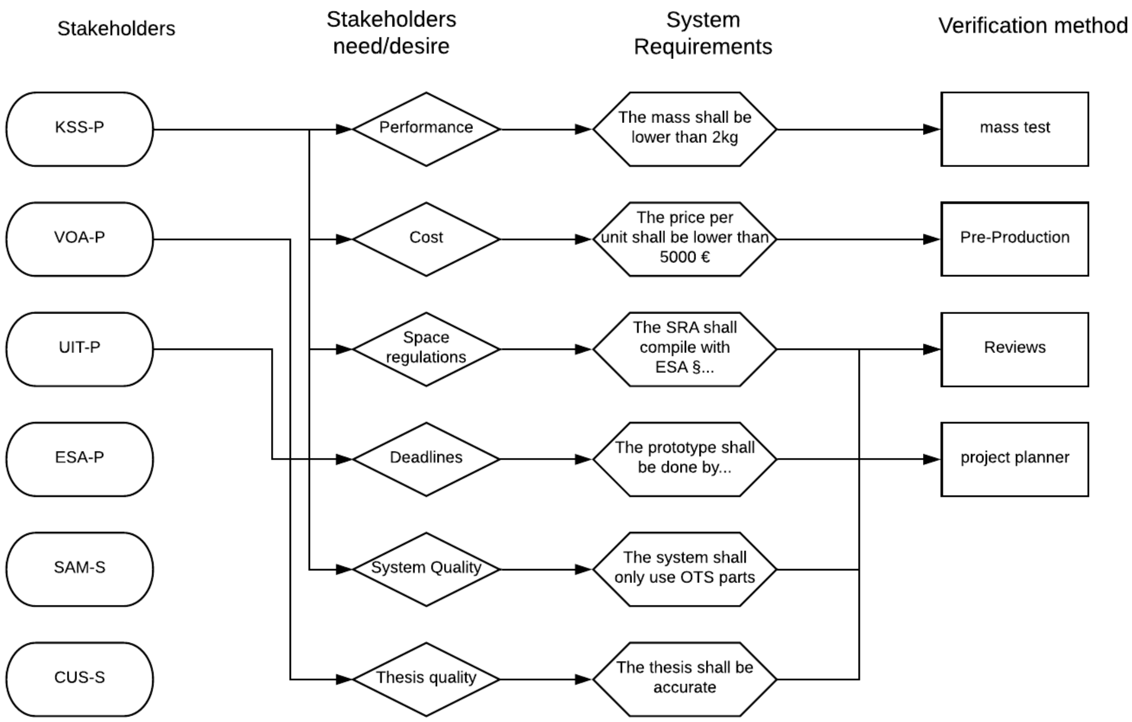

Figure 16: Requirement identification process.

The identified requirements are divided in to three sub-categories, environmental requirements, technical requirements and thesis requirements with the following designation EREQ, TREQ and REQ. In addition, each requirement follows the following guidelines:

Table 4: Requirement guidelines.

Requirement grade based on owner:	
A	The owner is very important
B	The owner is important
C	The owner is not that important

How important is the requirement to the system stability:	
A	Needed for stability
B	Plausible needed for stability
C	Not needed for stability

How is the requirement be validated/verified:	
T	By Test
A	By Analysis
R	By Review

Table 5 shows and example on how the requirement standard is set and how to read the table.

Table 5: Requirement example.

Nr:	**Requirement**	**Class**	**Originator**	**Verification method**	**Evaluated**	**Compliance status**
TREQ-1	The SRA must have a hollow shaft with internal diameter of 30.00mm or more.	AA	KDA	AR	TBD	TBD

Observe that the requirement is a technical requirement with requirement ID TREQ-1 and class of AA meaning that the requirement is very important with respect to a major stakeholder (originator) and stability of the system. The requirement can be verified by both analysis or review. In the evaluation post it states TBD meaning that where the requirements are to be verified is not determined. The compliance post states if the requirement is compiled or not. In this case no verification method is applied and is to be determined.

All requirement can be found in Part A, sub selection 4.1.

In the same way, verification and validation methods are being made. Verification methods can be done by testing, analysis or review. Recall that each requirement has a designated verification method. This will ensure that the system-performance at the end of the thesis are being met. Table 6 and Table 7 shows how the verification is executed in an example.

Table 6: Requirement to be verified example.

Nr:	**Requirement**	**Class**	**Owner**	**Verification method**	**Evaluated**	**Compliance status**
TREQ-1	The SRA must have a hollow shaft with internal diameter of 30.00mm or more.	AA	KDA	AR	TST-7 Part B, selection 3	TBD

Table 7: Test Example.

<table>
<tr><td>Test ID:</td><td colspan="2">TST-7</td><td colspan="2">Requirements to be tested:</td><td>TREQ-1</td></tr>
<tr><td>Pass criteria:</td><td colspan="5">The SRA must have a center hole lager than 30.00mm</td></tr>
<tr><td>Test method:</td><td colspan="5">Analysis or review</td></tr>
<tr><td>Execution:</td><td colspan="5">Design review.</td></tr>
<tr><td>Result:</td><td>Not tested</td><td>Date:</td><td>-</td><td>Sign:</td><td>-</td></tr>
<tr><td>Comment:</td><td colspan="5"></td></tr>
</table>

In addition, to verify the system at the end, some QDR and QDA methods are used and explained in Table 8.

Table 8: QDR and QDA.

QDR	QDA
A quick design review is done rapidly when needed. Example, when designing the bearing house, a QDR can be executed to ensure that the house can fit the bearings. No documentation is needed for QDR's.	A Quick design analysis is done rapidly when needed. Example when estimating the gear ratio in relation to bearing friction and motor selection a QDA can be done by a simple simulation to ensure that the gear ratio is correct. No documentation is needed for QDA's

QDR and QDA is not seen as verification/validation method but guidelines to design correctly.

All planned tests for verification and validation can be found in Part A appendix 7.5.

3. Part B – Design and Construction

3.1. Objective, Focus Areas & Results

The main goal of Part B is execution of the translation of input to physical product prototype. Desired guidelines, desires and more from Part A should be implemented during Part B. I say should because several "needs" may interfere or compromise with other subsystems. This will be "worked" out to the best solution in this Part B. In other words, the Blackbox, Part B is trying to fulfill everyone and everything at the same time, for the best resulting WG-SRA. The focus area is therefore to obtain several ideas, look in to given sub-solutions and solutions and end up with a concept and a prototype.

The general process used in Part B is shown in Figure 17 while the most important result from Part B is the fully functional prototype as shown in Figure 18.

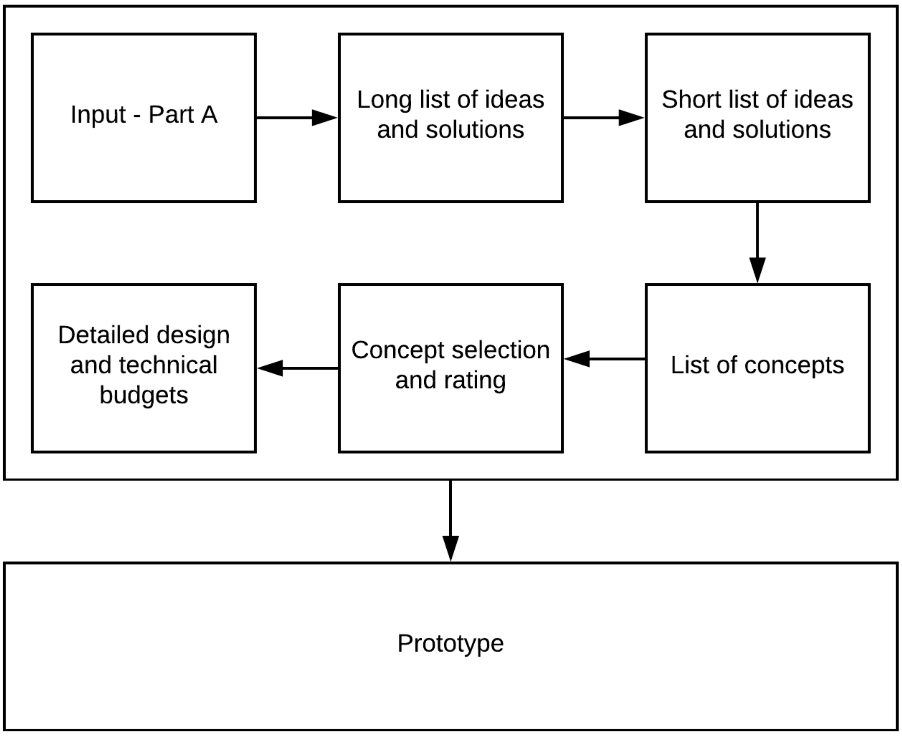

Figure 17: Design Process.

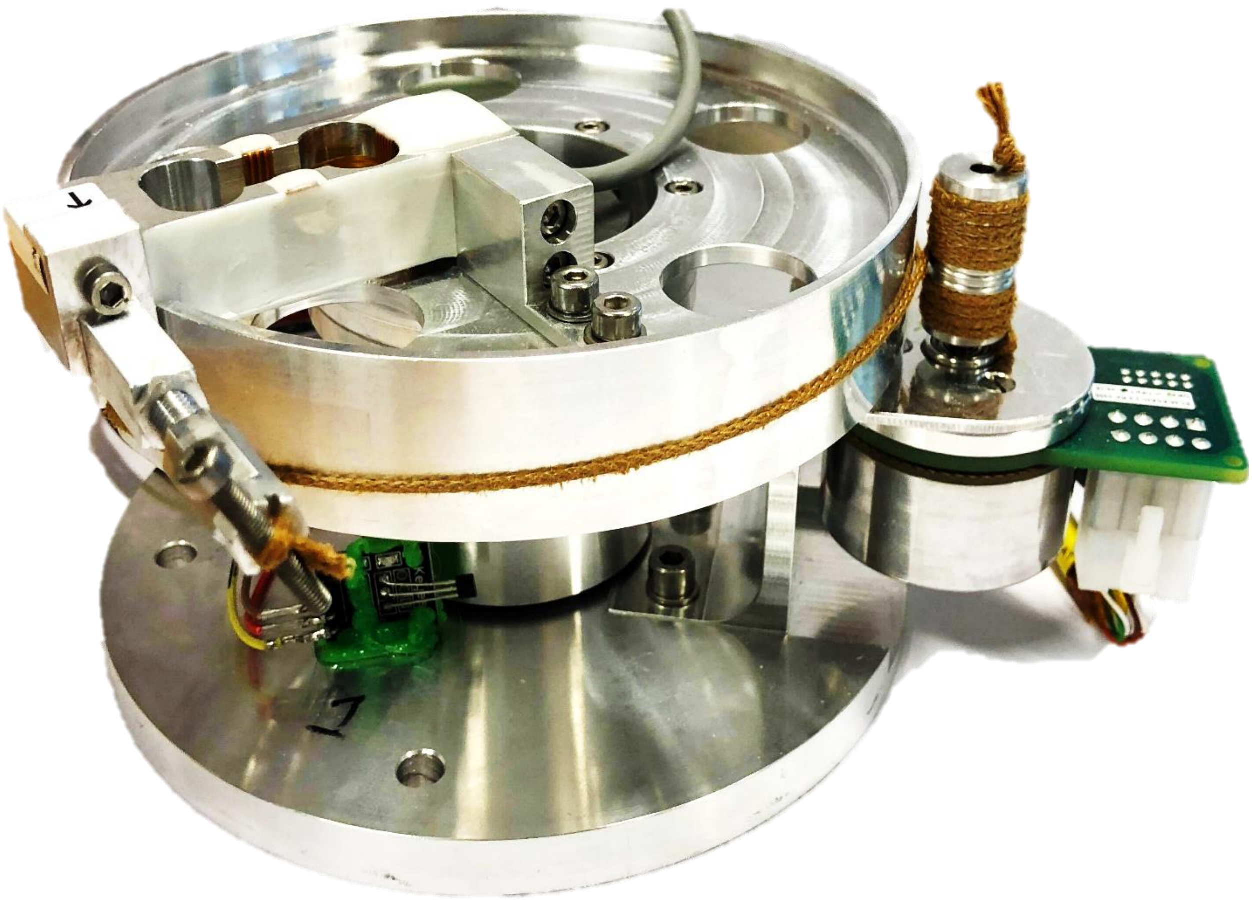

Figure 18: WG-SRA Prototype.

3.2. Ideas & Concepts

After a comprehensive analysis of the input, several ideas were "found" and discussed. Idea 6, 8 and 10 was the most feasible ideas and renamed concept with the following names, Jupiter, Mars and Pluto. All ideas, and the full study can be found in Part B, selection 2.

Concept Jupiter consist of two wires, one wire fixed to the large pulley and to the pinion. The other wire is fixed to the preload mechanism at the load cell and to the pinion in a crossed belt configuration. The main advantage for this concept is the simple preload mechanism and the possibility to have infinite length of the wire – no limits regarding how much you may "pull" in the wire. As for disadvantage, the hold torque in the preload mechanism may not be stable over time, and the preload mechanism itself is quite complex and not "of the shelf". Figure 19 shows concept Jupiter.

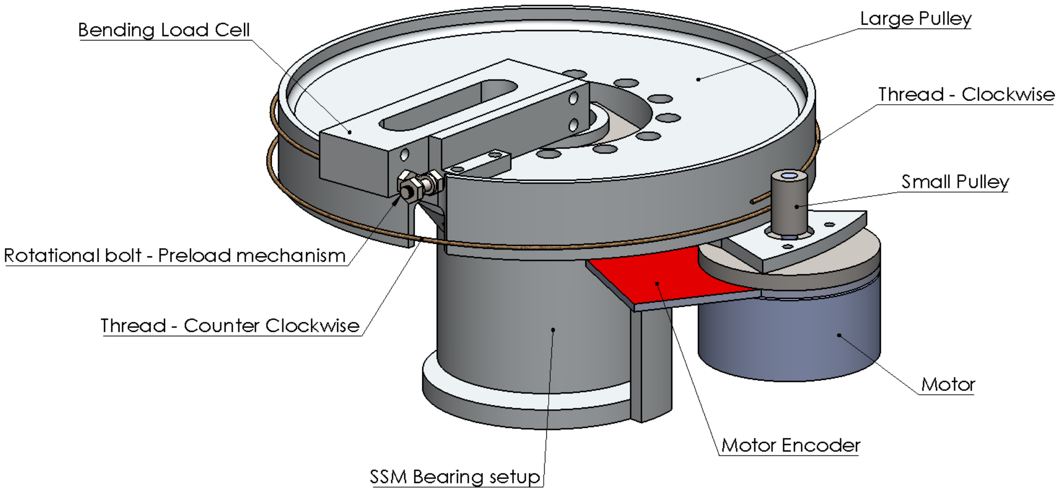

Figure 19: Concept Jupiter.

Concept Mars is almost the same as concept Jupiter. The difference between Mars and Jupiter is that the preload mechanism is not located on the load cell. Instead the preload mechanism is located at the underside of the large pully. It has the same advantages as Jupiter, however it has some major disadvantages. The preload mechanism is "unreachable" to rapid adjust, and may be hard to maintain in addition to the other disadvantage for this preload mechanism. Figure 20 shows concept Mars.

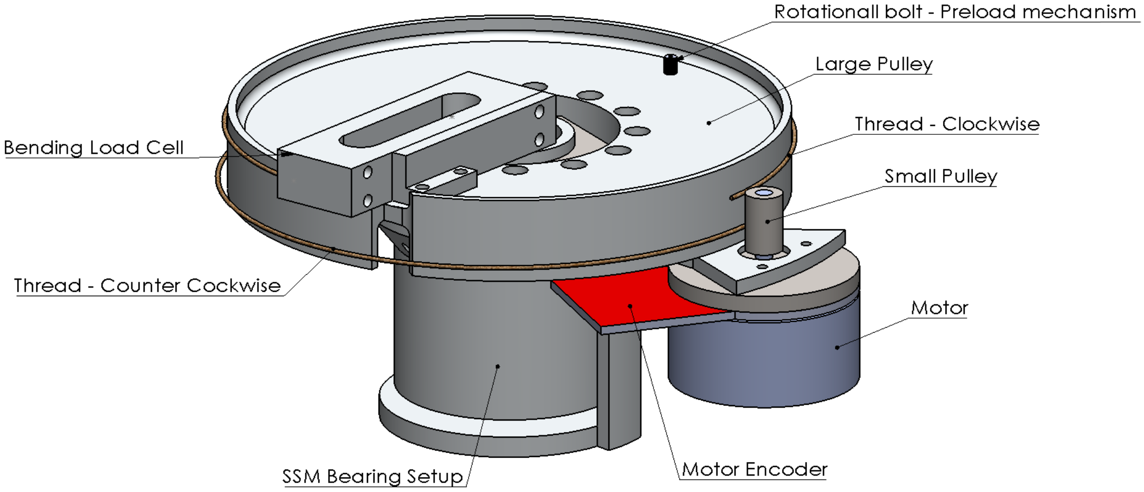

Figure 20: Concept Mars.

Concept Pluto consist of the same mounting and wire layout as concept Jupiter, the difference is that a new preload mechanism is applied. This preload mechanism is pretty much like a traditional hollow screw that axially displace the wire instead of "pull" it in. This type of preload mechanism is much stiffer than the rotational one. The major drawback is that the wire must be pre-fitted since infinite length cannot be achieved. Figure 21 shows concept Pluto.

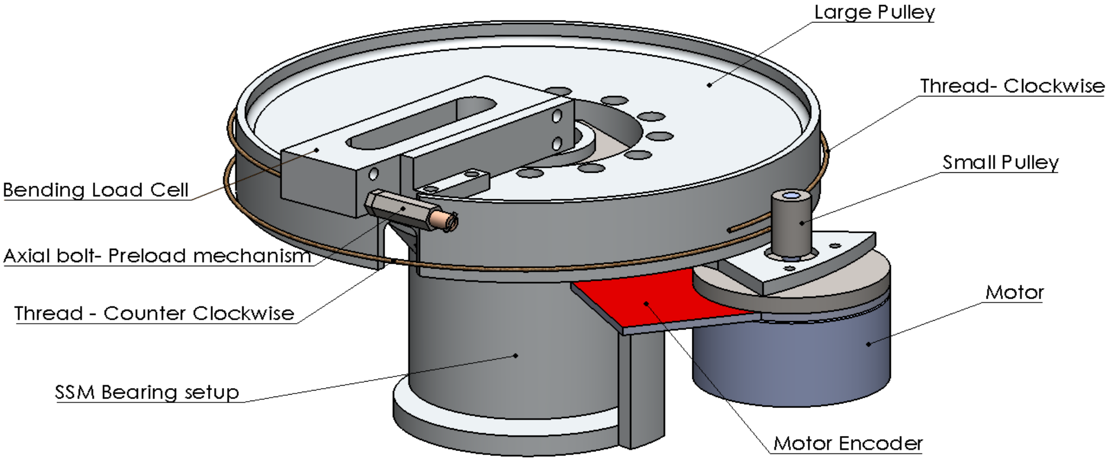

Figure 21: Concept Pluto.

After the concept development and discussion, a selection matrix was made to select the best solution. The criteria for the concept selection is shown in Table 9.

Table 9: Criteria's and weighting for Concept Selection.

Criteria:	Unit:	Weight:	Explanations:
Preload hold torque:	Nm	20%	Highly weighted. Hold torque is very important to keep the required tension in the wire. This affect the system stability. Slack wire equals increased pointing error and directly violates several requirements.
Preload adjustability:	mm	7.5%	Medium to low weighted. Preload adjustability is important to the system but does not interfere with system stability.
Integration complexity:	-	10%	Medium weighted. Integration complexity is important to the system but does not interfere with system stability.
Maintenance:	-	22.5%	Highly weighted. Maintenance is very important to keep the required tension in the wire. This affect the system stability. Slack wire equals increased pointing error and directly violates several requirements. It's feasible to believe that the wire must be adjusted several times during lifetime testing.
System complexity:	-	10%	Medium weighted. System complexity is important to the system but does not interfere with system stability.
Wire fitting:	-	10%	Medium weighted. Wire fitting is important to the system, and it can simplify the preloading process. However, this does not affect the system stability.
Supplier cost:	€	10%	Medium to high weighted. Supplier cost does not affect the stability of the system but is a large requirement regarding total cost.
AIT cost:	€	10%	Medium to high weighted. AIT cost does not affect the stability of the system but is a large requirement regarding total cost.

The resulting concept selection matrix is shown in Table 10. With the following note. The preload hold torque and maintenance of the wire driveline is very important, both for endurance under lifetime test and system stability. Because of this the concepts are fairly depended on this criteria's.

Concept Jupiter obtain a total concept score of 3.475. It loses score due to the preload mechanism and cost criteria's. Concept Mars obtained a concept score of 2.6 and is the "worst" concept. It loses the same scores in the same criteria's as concept Jupiter but in addition have poor maintenance abilities. Concept Pluto is overall better than the other concepts with only a small drawback regarding wire fitting.

Concept Pluto is the winning concept in this Pugh's selection with a score of 4.275. The result was presented to KSS during several skype meetings, concept presentations, several delivered STL files and discussions/iterations. Concept Pluto was accepted by KSS with respect to my investigation.

Table 10: Pugh Selection Matrix.

Pugh's Concept Selection Matrix

			Concept alternatives		
Criteria:	**Unit:**	**Weight:**	**Concept Jupiter**	**Concept Mars**	**Concept Pluto**
Preload hold torque	Nm	20 %	3	3	5
Preload adjustability	mm	7,5 %	5	5	5
Integration complexity	-	10 %	3	2	4
Maintenance	-	22,5 %	4	1	4
System complexity	-	10 %	4	3	5
Wire fitting	-	10 %	5	5	3
Supplier cost	€	10,0 %	2	2	4
AIT	€	10,0 %	2	2	4
Sum		**100 %**	**3,475**	**2,6**	**4,275**

3.3. Detailed design & Wire Configuration

The concept is now selected, and implementation of requirements and system-needs is executed, with the goal of a functional prototype. First the performance part of the system is being designed. The boundaries regarding performance is limited to the pre-selected motor. The motor is from Maxon Motors with designation, EC45 Flat 70W, and with a system requirement TREQ-5 from Part A, with 8W power consumption at maximum. By analysis the following watt-torque graph is generated.

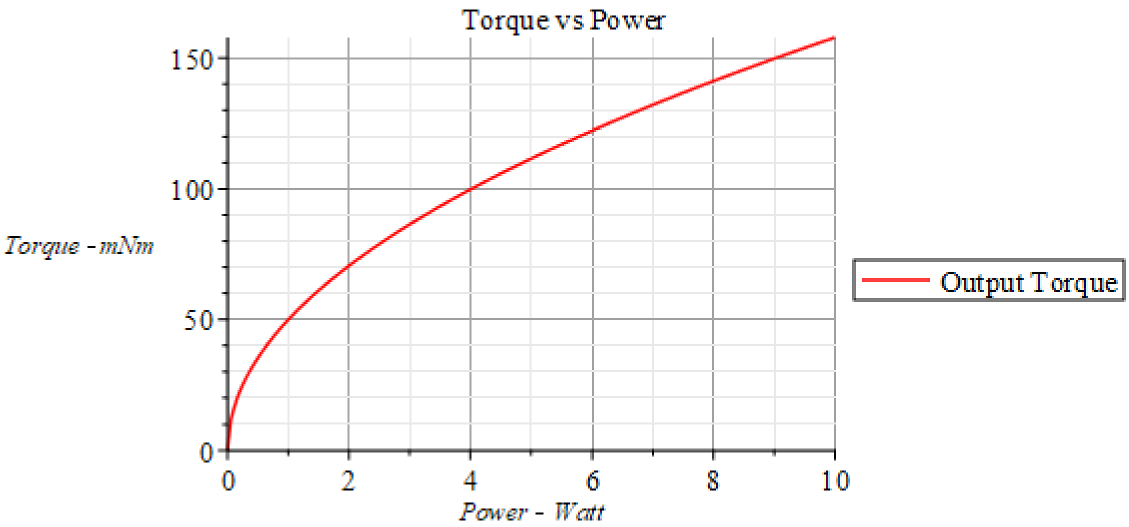

Figure 22: Torque vs Watt.

This implies that the motor can produce at maximum 140 mNm within the 8W requirement. Now recall that the angular frictional torque momentum from the bearings was estimated to 172.8 mNm in each bearing and with ECCS standards 1077.42 mNm for both bearings. Thus, gear ratio is therefore designed to be

$$\text{Minimum gear ratio} = \frac{T_{\text{min}}}{T_{\text{motor}}} = \frac{1077.42}{140} = 7.695.$$

In collaboration with KSS, final gear ratio is selected to be 1:10, to adjust for uncertainties and not having the motor at maximum allowable power continuous. (The motor produces 110mNm with 1:10 in gear ratio.)

The second part of the detailed design is control system for the endurance test. A basic code is made based on input and outputs of sensors, making the system to sweep a radius of 0-180 deg with the desired acceleration of 90 deg/s^2. The sweep code is made with Arduino and C++ while the performance related to velocity and acceleration with ESCON 50/5 speed controller.

In the third part of the detailed design, the pullies are discussed. Based on a report given from KSS by Kodyna, some design features are suggested. The large pulley should be free, no tracks or grooves to guide the wire. The small pulley should be a helical gear with a profile to fit the wire and to guide the wire. By QDA, QDR and discussion with KSS, the pinion diameter size was selected to 14mm, and designed with ability to give an output angular displacement of $\pm 190°$. The resulting design is illustrated in Figure 23.

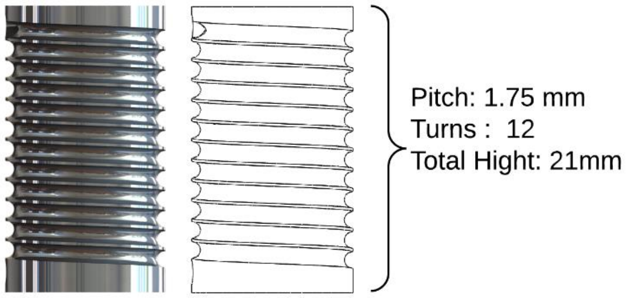

Figure 23: Pinion Worm Gear.

The output pully is highly simple but dependent on the input pully – pinion. Figure 24 shows the resulting output pully.

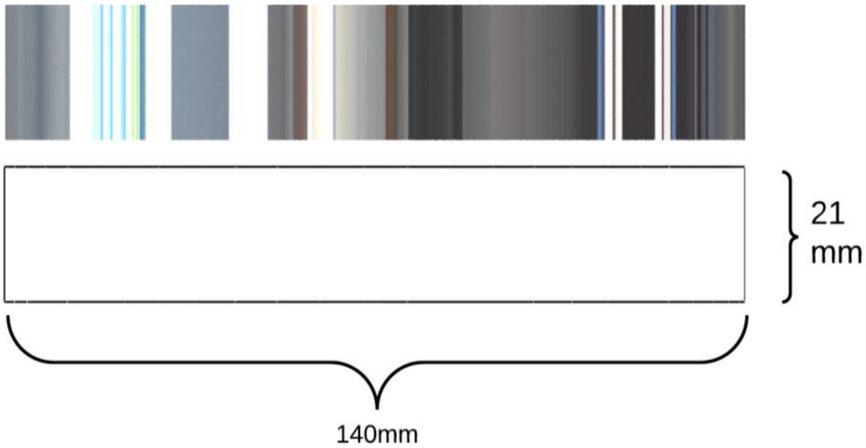

Figure 24: Output pully.

The forth part of detailed design, is the bearing setup. This setup is the same as in the bachelor thesis by SSM. It uses normal deep groove ball bearings but pressed in a way, so they behave like angular deep groove ball bearings. Figure 25 illustrates the bearing setup and contact angles. See Part B selection 3.5 why it is done in this way.

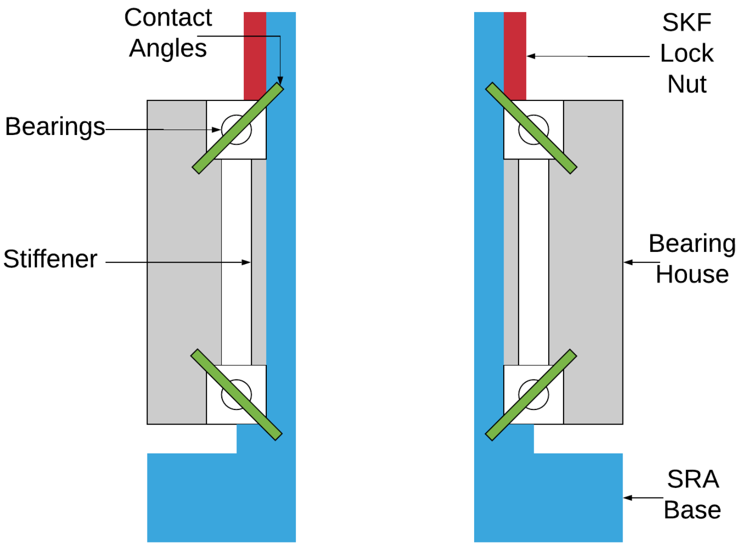

Figure 25: Bearing setup.

The last part of the detailed design of the system is material selection. A small analysis is made, but ECSS standards for material selection is mainly used. Ball bearings and fastener are made from stainless steel while constructional parts are made from Aluminum. The material for the wire is preselected and is known as PBO or Zylon. Several Zylon wires was obtained, and different test executed. A friction test of Norsk Fletteri wire number 1 is executed, with over 1 mill cycles – no errors, and additionally a tension test. This wire is the only wire that was tested properly and selected for the lifetime test. Normally all wires should have been tested, but due to limited time only this wire was executed in the friction test.

Finally, the wire configuration is discussed, crossed belt configuration was selected during ideation, pully sizing during detailed design, and wire type during tests and discussion. The last but most important part is preload in the wire. To ensure that the wire keeps it integrity – no slack side. An analysis was made. We know by calculation that the force in the wire due to torque is

$$F_{\text{thread}} = \frac{T_{\text{motor}}}{d_{\text{pinion}}} = \frac{110 \text{ mNm}}{14 \text{ mm}} \cong 8 \text{ N}.$$

This implies, that with no preload the force is $\pm 8N$. This means that we have one tight side (8N) and one slack side (-8N, the amount of tension needed to remove all slack). To counter this, the slack side and the tight-side must have positive numbers. In other words, the preload is correct when the tension is above 0 on both sides. Based on this the preload must be over 8 N in stable state. Therefore, suggested preload is 16N. This because the wire “lives” and must be broken in – we wish to remove all creep so that the wire stabilizes at zero slack.

Now the concept is fully implemented, and a prototype can be made after validation trough technical budgets.

3.4. Technical Budgets

Several budgets were made, to ensure that the fully implemented concept is ready for prototype status. Mass, strength, torque, performance, pointing, and cost budget was discussed with the following results.

Table 11: Technical budgets.

Technical budget:	**Purpose:**	**Result:**
Mass Budget	Validate mass related to requirement.	A total of 994g for the complete wire geared small rotary actuator and a total of 1478g including test equipment.
Strength Budget	Validate strength accordingly to ECSS standards.	A safety factor of more than 1.2 was found with the respective load scenario.
Torque Budget	Validate torque and power related to requirement	A factor of safety related to limited power and torque was found to 1.29.
Performance Budget	Validate performance related to requirement	Performance is accordingly to requirement within the torque budget.
Pointing Budget	Validate pointing error related to requirement.	Pointing error is found to 0.0218 deg. Note that this budget is highly estimated and should be iterated.
R&D Cost Budget	Project cost tracking.	A total estimate of 4849 Euro in cost for the project is found excluding labor.
Production Cost Budget	Mass production cost tracking.	A total estimate of 4900 Euro in cost for mass production including labor is found.

3.5. Prototype status and remarks

Some improvement points were found. Figure 26 shows the location where the wires are connected to the output pulley. These points have some guide tracks for the wire to ensure that the wire is not exposed to rough edges, or steep angles. This track seems a bit too small as the wire is very close to the edge. Because of this the tracks should be redesigned to be 100% sure so that this cannot compromise the integrity of the wire. Figure 27 shows the angle of the wire between the load cell and the guide track. The track should be designed in a way so that the wire is not exposed to any sharp edges. Right now, the design is slightly off and the angle of the wire a bit to sharp. This results in “connection” between the wire and unwanted “metal”. Because of this the guide track should be redesigned to match the angle 100%. Figure 28 shows the motor and motor bracket. The forces on the motor is low due to equilibrium, however KSS suggested that the motor bracket should be reinforced with some ribs on the side to keep maximum stiffness. In addition, on the pully, one wire had to be skipped to ensure that the wires are not in contact, this is a small design error and hard to verify without testing because of different wires and styles. Because of this the pitch should be increased slightly.

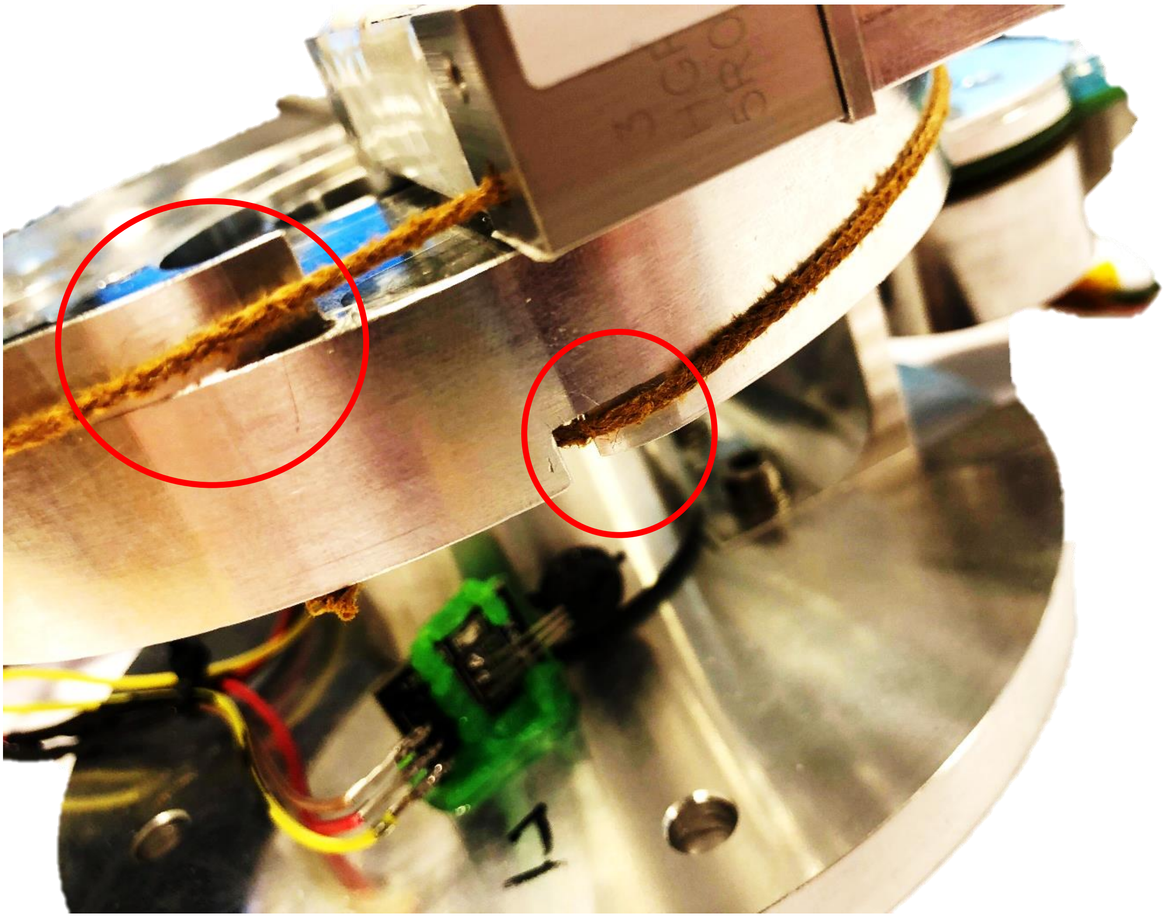

Figure 26: Wire guide tracks.

Figure 27: Wire drive angle.

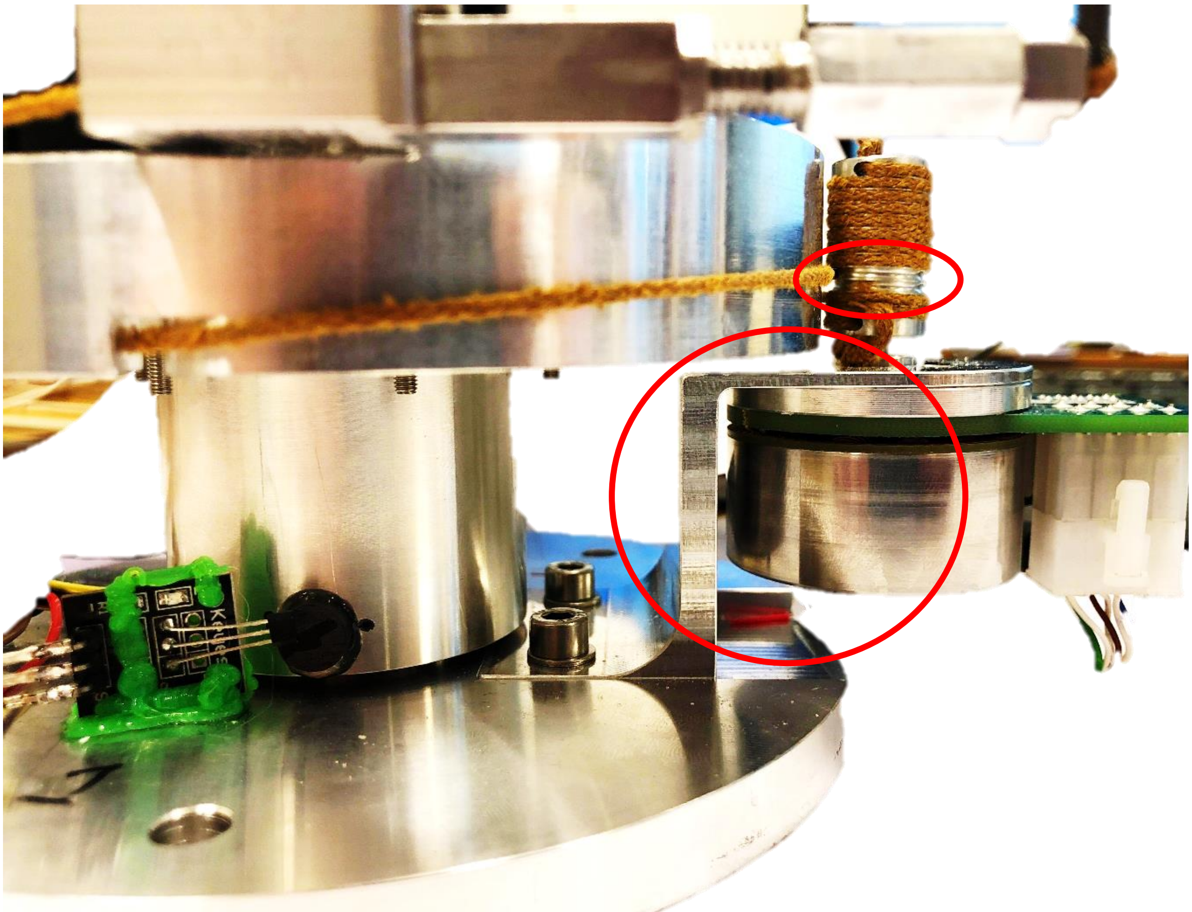

Figure 28: Motor and motor bracket.

4. Part C – Hard testing and verification

4.1. Sub level testing and results

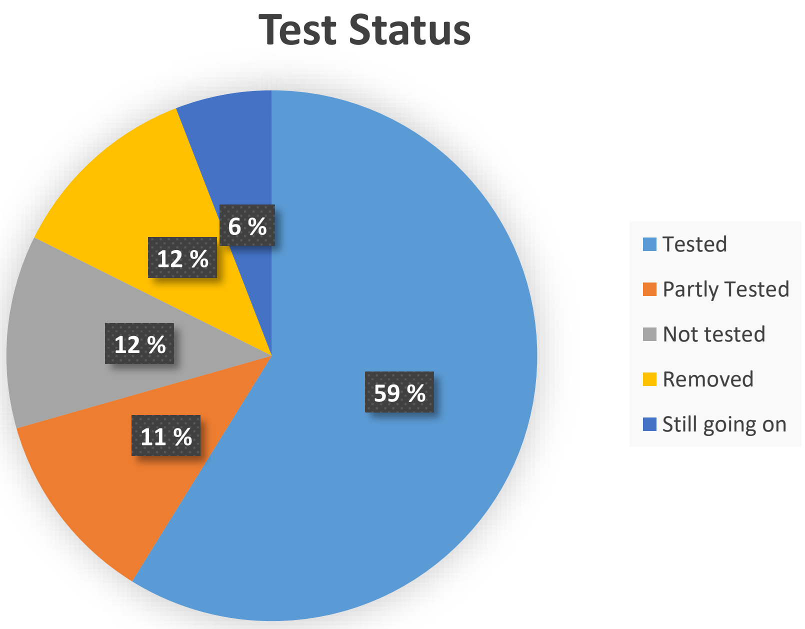

Figure 29: Test status.

59% of the planned tests are tested, 11% of the planned tests are partly tested. 12 % are not tested, 12 % is removed and 6% are still going on. The reason for 11% of the test only being partly tested is because just aspects of the "feature" is tested. Example TST-1 and EREQ-1 and EREQ-2 "The system shall withstand operation in temperatures between [-25, +65] °C, both in function and not in function". The full spectrum is not tested, only ambient temperature. Note that this does not affect the "on-Earth" performance. The reason for 12% not tested is because the requirement has not obtained a test method. Example TST-6 and EREQ-7 "the system shall not be affected by LEO environment". During this thesis the resource needed for doing this test is not available. This test does not interfere with the "on-Earth" performance. The reason for 12% of the test are removed is because it's not relevant anymore. Example TST-4 and EREQ-5, "The system shall not be affected by humidity levels of TBD". This requirement was removed by KSS because its relevancy related to the main goal.

The last 6% being still going on is the lifetime endurance test and discussed in selection 4.3.

4.2. Pre-lifetime testing and results

Based on experience during the thesis. Creep is an issue. The following process is applied to reduce the risk of creep. First the knots are secured and glued. This to make sure it will hold its integrity and not "loosen". Second the wire is loaded with a given preload and set overnight. Third the wire is readjusted if needed and set in cycles overnight. Forth the system is set in the vacuum chamber, and set to run for 5 hours, readjust if needed. And finally, a pre-test in vacuum. Hopefully all initial creep is now removed, and lifetime test can be executed. If the tension in the wire decrease below acceptable levels, the test must be stopped, wire adjusted, and test restarted. Figure 30 shows the results and process.

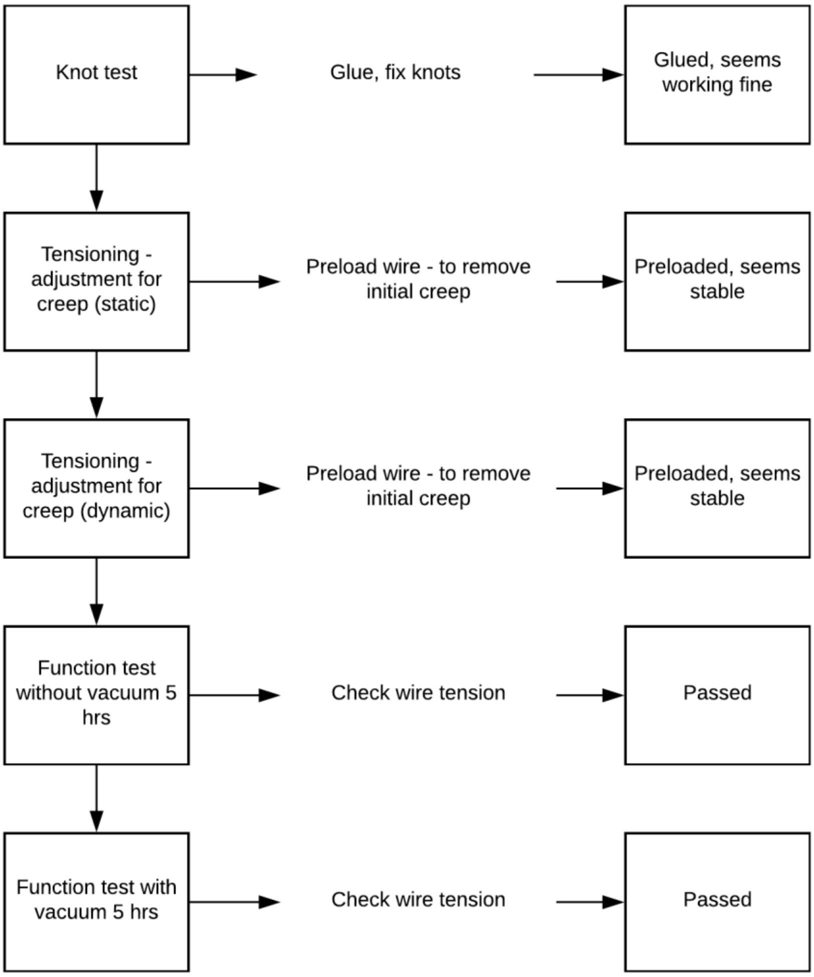

Figure 30: Pre-lifetime test.

4.3. Lifetime test

The test rig is the developed SRA. Recall an output shaft of 140 mm in diameter, and an input shaft of 14 mm with a pitch of 1,75 mm, 12 turns. With a total angular friction of 345,6 mNm and surface roughness of N5. The test rig and equipment's are shown in Figure 31 to Figure 33

Figure 31: Tensioning monitor

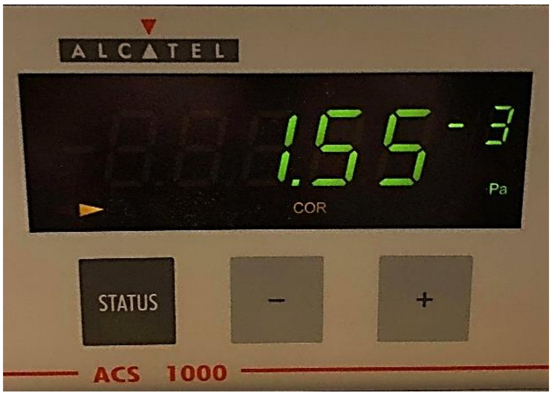

Figure 32: Pressure monitor

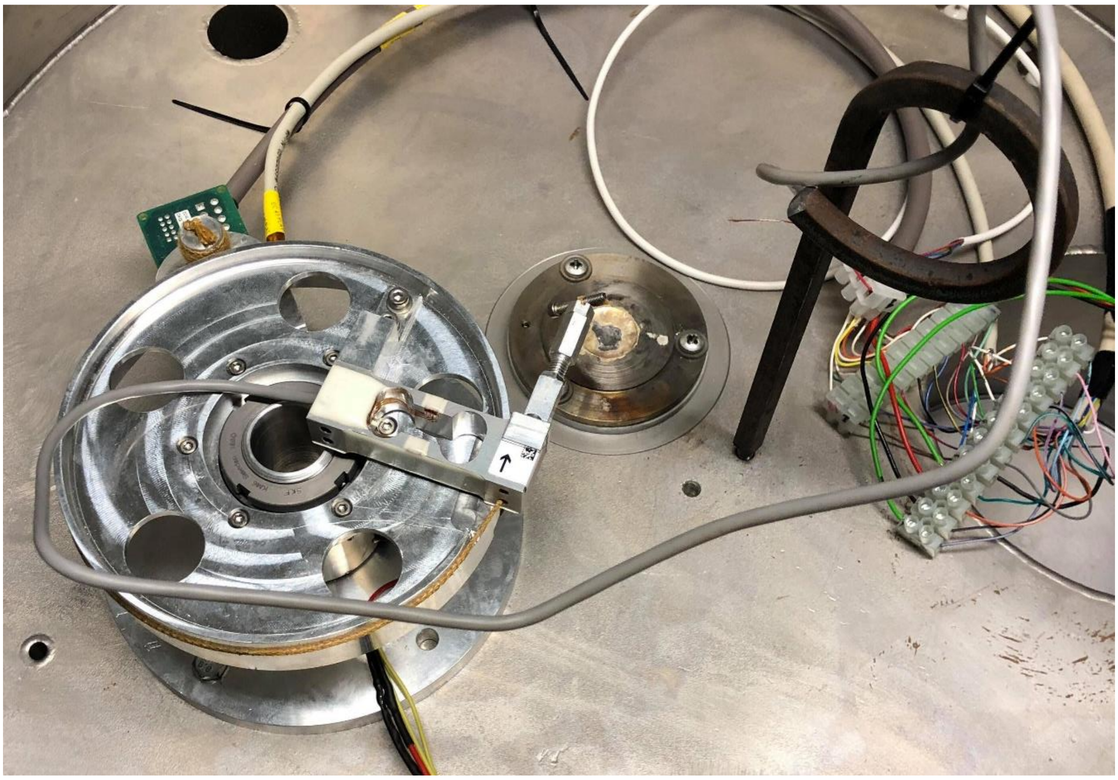

Figure 33: Test setup

4.4. Description of test wire.

The wire is the NORF-1, this was the only wire that executed friction test. The NORF-1 wire has the following specifications:

- Circular diameter of 1.0mm
- Fiber tensile modulus of 1650 cN/dtex
- Braided with 8 strands, in “flag line” braid
- Custom braided from Norsk Fletteri.
- Fibers directly from Toyobo.
- Wire tensile strength from test at Norut was estimated to 1250 N at approx. 43 mm elongation on a 385mm long wire.
- Completed over 1M cycles in adhesive friction test – no major remarks.
- NOT PROTECTED AGIANST UV BEAMS!

4.5. Procedure followed.

- Pre-lifetime procedure to reduce creep was executed.
- Test started without monitoring preload, an unspecified preload was given – no slack observed. Vacuum applied.
- Load cell manual calibrated by datasheet by HBM.
- Test running for approx. 350,000 cycles, loadcell now connected. Tension above suggested minimum.
- Wire tension and vacuum pressure monitored twice a day.

4.6. Test result

In collaboration with KSS, the following result is presented. A noticed squeaking noise might come from poor lubrication or too high preload in the bearings. However, this did not affect the test results. The wire is slightly surface damaged and carved out some metal dust but still very stable. The drop in wire tension between 550000 and 750000 cycles has no explanation, however its feasible to believe that this is due to monitoring issues, grounding or electrical failure within the equipment. This because the graph is very stable before and after the drop. I also conclude that the system was designed correctly, and was build right, because of this result. It did what it was supposed to do.

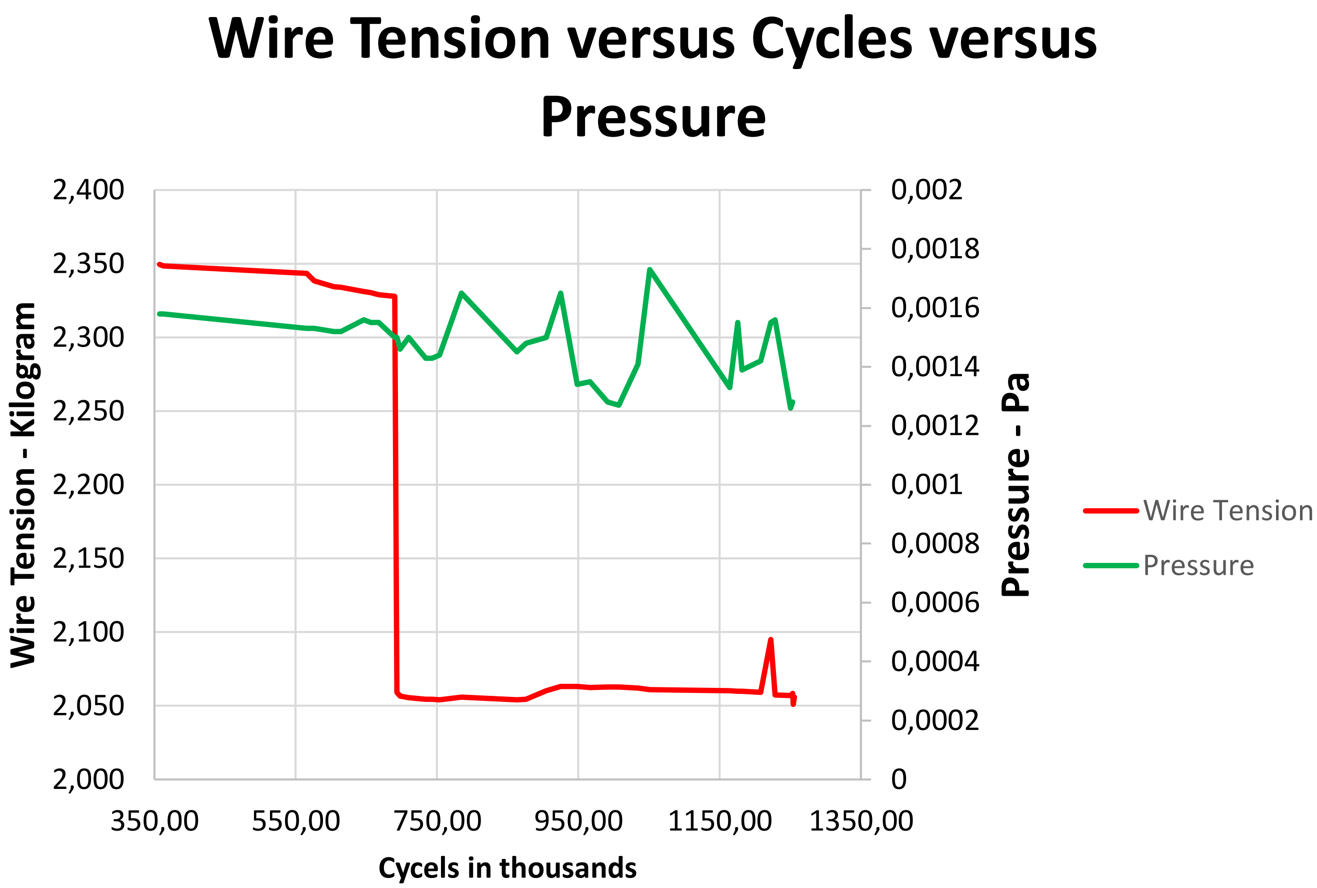

Figure 34: Wire Tension vs Cycles vs Pressure

Figure 34 shows the resulting tensioning vs cycles vs pressure. Note that the drop is very clear and "hard".

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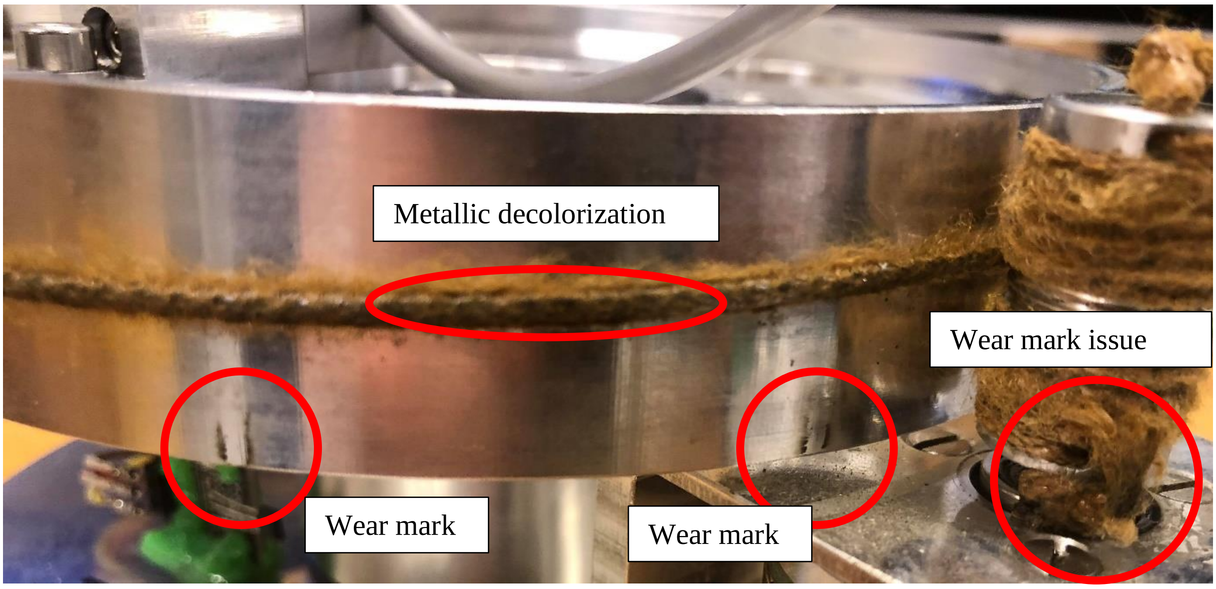


Figure 35: Minor knot failure

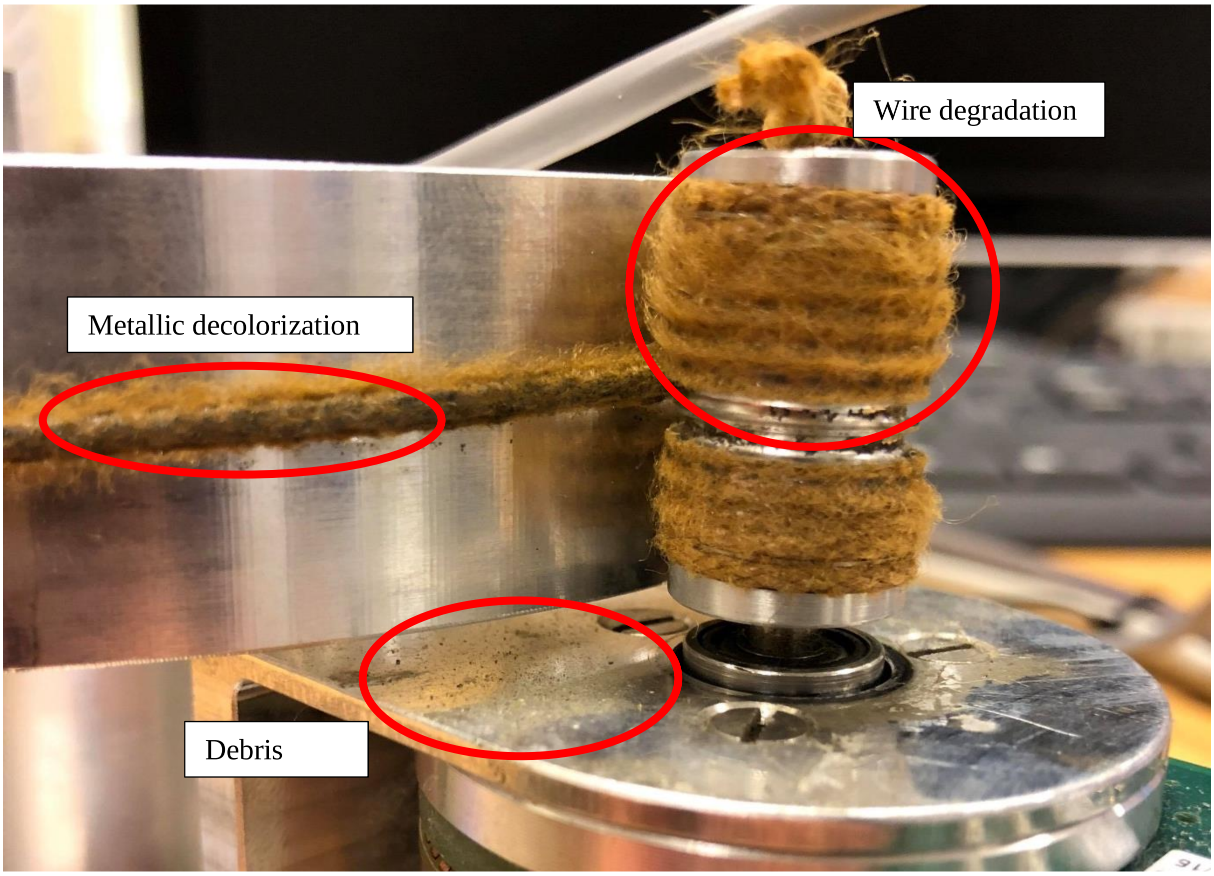


Figure 36: Wire degradation

5. Part D – Finalizing and summary

5.1. Requirement and stakeholder status

After an investigation of requirements, we can say that 72% of all requirements is implemented or partly implemented. 20% of the requirements is not evaluated or removed while only 8% of all the requirement is not met. A cake diagram illustrates the requirement status for the product and thesis.

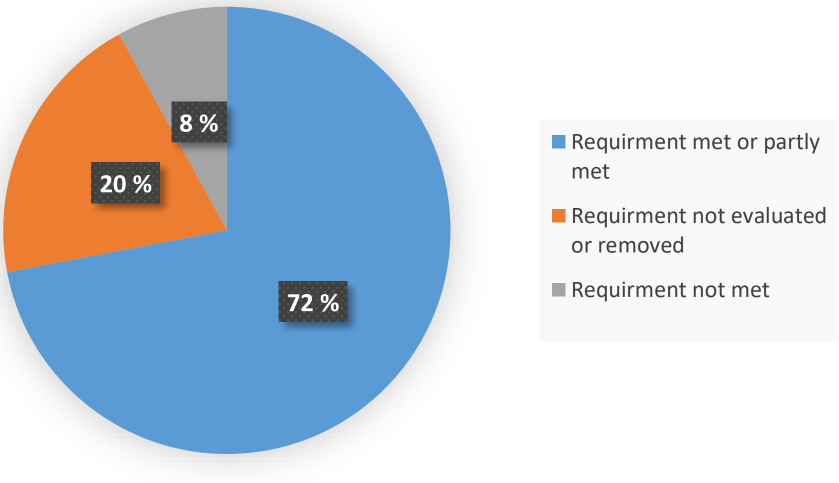


Figure 37: Requirement status.

The reason for partly implemented or partly met can be several things. An example is requirement TREQ-2 and the respectively test TST-8 related to pointing error is only partly met. This because the pointing budget is weak, and not validated / discussed with KSS. However, it gives a highly estimate on the behavior.

As for the stakeholders some small adjustments are made. UiT has increased in influence, mainly because the lifetime test is executed at the school with school equipment. In addition, customer segment of the stakeholder increased slightly in interest mostly due to the news of Space X's Starlink project. Figure 38 graphically show the change in stakeholder's influence/interest.

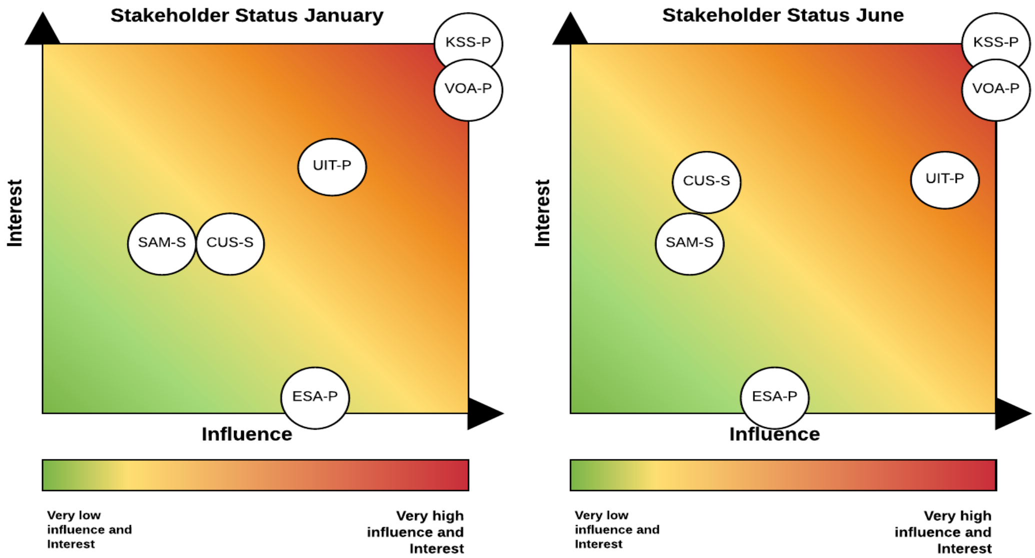
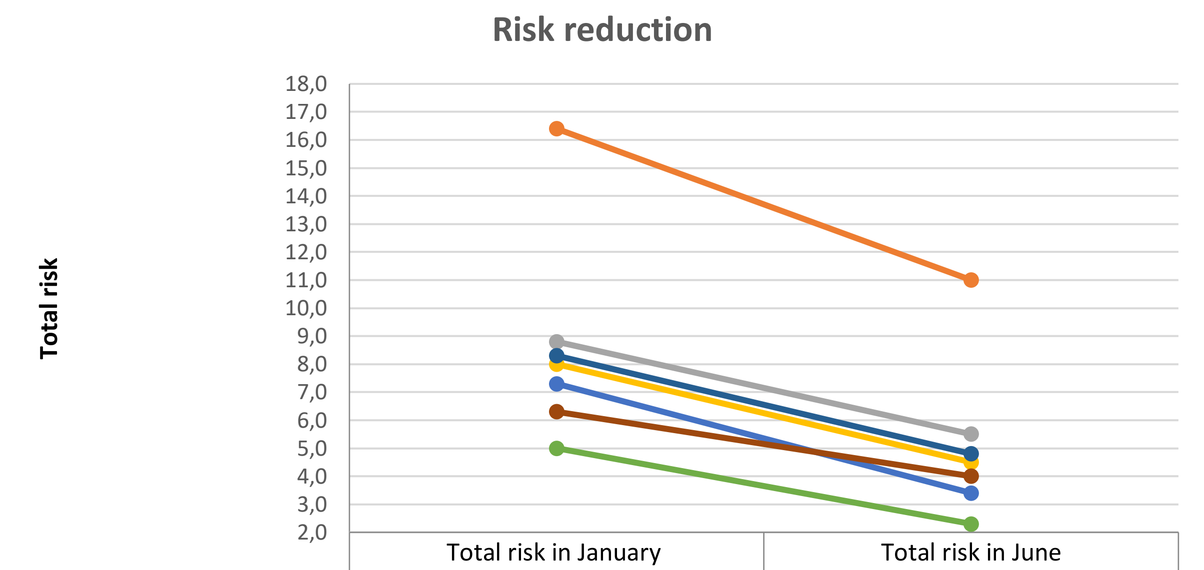


Figure 38: Stakeholders changes.

5.2. Risk status

The risk for the project is reduced by 41% going from 8.6 in score to 5.0. This means that the project state at this point is acceptable, but measure should still be taken to eliminate risk. This is normal, and more iterations especially related to the technical part should be executed. Figure 39 shows which and how much each segment is reduced. In Part D, selection 3, information related to this can be found.



	Total risk in January	Total risk in June
Space Environment	16,4	11,0
Operational Risks	8,8	5,5
Cost risks	8,0	4,5
Schedule risks	7,3	3,4
Safety Risks	5,0	2,3
Development risk	8,3	4,8
Human resources risk	6,3	4,0

Figure 39: Risk Results.

5.3. System status

All segments, stakeholders, requirement, risk and product seem stable and feasible and therefore is the total conclusion of the system. Everything seems to be working perfectly, every stakeholder, requirement and more is being satisfied in the right amount and in the right way. I conclude because the test rig and wire can do more than 1200000 cycles which is maximum within the time limit, the system is very successful.

5.4. Thesis conclusion

The total goal for this thesis was to develop a small rotary actuator with wire driveline for use on small antenna pointing mechanisms intended for usage in low Earth orbit. The main reason for this was to investigate the possibilities of wire driveline to replace traditional gear transmissions. In detail recall the project description:

"In the 21th centaury the need for lighter, better and cheaper low Earth orbit solutions is increasing due to the increase of more satellites, rockets and systems are being launched every day, i.e Space X. Kongsberg Space Systems is one of the larges divisions of space solutions in Norway, delivering to ESA and more. In fact, Kongsberg Space Systems is Norway's largest supplier of space equipment's to ESA.

To meet this increase for space applications Kongsberg Space System (KSS) wishes to develop a light, high performance, wire geared actuator for small rotary actuator systems."

System Engineering was the applied tool for meeting this goal. By applying System Engineering, the thesis was divided into 4 different parts, with its own sub-goal and a main thesis goal.

In Part A, the main goal was to create a foundation, an input or set of rules for the system. In this "handbook", details such as stakeholders, requirements, risk, initial design and more was created. All with the purpose to break down the project description into sub systems. As discussed in Part A, this Part A was very successful. Several stakeholders were found and rated, risks identified, initial detail design executed, and requirements stated.

In Part B, the main goal was the translation of the input in Part A to a physical product prototype. In this Blackbox (Part B), details such as ideation, concept selection, technical budgets and more was created. All with the purpose to use the "braked down" system in Part A, to build up the system and match the product desired. As discussed in Part B, this Part B was very successful. The obtained input was very good from Part A, and it was easy to understand. This resulted in a very good and systematic execution of Part B. The resulting prototype looks perfect, by pictures shown in Part B and by investigation. During assembly, every manufactured part was easily connected, and Kongsberg Space System was satisfied with the prototype. This also indicates and empathize that my design and production drawings was good and successful.

In Part C, the main goal was to iterate, and verify that the outcome of Part B was scientifically connected to Part A. In this Part C the planned tests from part A on sub-level were executed according to its test method, and commented. 59% of the planned tests were tested, 12% removed, 12% not tested, 11% partly tested, and 6% still going on by 5 of June 2018. In addition, a pre-lifetime test was executed. This resulted in 73% of the tests being executed, if the removed test is excluded and the 6% test is included. Because of this the iteration and validation Part C were very successful. The last 6% test is the life time test and main goal of this thesis and will be discussed below.

In Part D, the main goal was to summarize the thesis based on the outcome of Part A, B and C. All with the purpose to see how the project changed, how good it was satisfied and to gain new input for future iterations. 72% of the initial requirements were met or partly met, 8% of the requirements were not met, and 20% not evaluated or removed. Minor changes in stakeholder's interest and influence were observed, and a risk reduction of 33% was achieved. Overall with 72% of the initial requirements met /partly met, and identification of changes, Part D was very successful and provide good information to future iteration.

Recall that 6% of the tests were still going on, on 5 of June 2018. This test directly investigates if this wire driveline can replace traditional gears in SRA's assemblies. The result of the test is execution of over 1,2M cycles, kept its preload integrity above 2.0 kgf and had a stable vacuum pressure. For this test to be accepted, 5M cycles had to be executed. Due to supplier issues, the test was not started in time, and can therefore only be partly accepted and verified. All in all, the obtained result seems very good, and it's feasible to believe that wire can replace traditional gears for WG-SRA. I think that the main issue is not related to creep, preloading or the wire its self, but external subsystems, such as knots, UV-beams, sharp edges and more. I therefore conclude that its plausible that Zylon wire in a driveline for SRA's can replace traditional gears for LEO applications – its highly feasible, and just imagine the global goal for the human kind:

What if in just 10 years, you can have 6G internet all over the globe, in space craft, in airplanes, on Mount Everest – everywhere to the same price! Recall Greg Wyler:

"While the cities and suburbs of developed countries have broadband access, over 50% of the world, including rural America, Europe and Asia, remain without reliable high-speed connectivity. The impact in emerging markets is even greater, where many are without access even at their schools or community centers. Internet access is critical for digital government, health and education, and lack of access impairs financial growth when markets cannot develop, trade and become economically relevant to each other. This issue impacts everyone, and together we can solve it." [3]

Wire – The – World

Figure 40: Satellite Constellations [13]

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