Dark Ages Lunar Interferometer

Deployment Rover - Suspension System and Transition Mecanism

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Preface

This is a degree thesis done by two mechanical engineer students on Halmstad University during the spring of 2014. It is an education that lasts 3 years. The degree theses are often in collaboration with a company. The company of this thesis is Nasa. The project in this thesis is a part in the development of a rover with the purpose to operate on the far side of the moon, deploying an instrument for science research.
Abstract

This thesis is a continuation of last year's work and it builds on earlier construction of a rover that will deploy an interferometer on the far side of the moon. The project is done in collaboration with (JPL) Jet Propulsion Laboratory in Pasadena, California.

Given the size of the mission, accuracy and time limit project has been split into several smaller projects. The areas that are the focus of this project are the suspension and the transition system. The transition system that is originated from the stage when the rover transforms from the transit mode to ready mode, and the suspension system, are in this thesis work presented by detailed conceptual design. The next step, not mentioned this thesis work, will be to perform a primary structure design on the details.

The project owner's ultimate goal is to create a better understanding about the origins of the universe and its continual changing. This would give scientists an opportunity to study some of the most fundamental questions that are still are waiting for answers.

Together with a group of energy engineers, Gustav Andersson and Emil Ericsson, we were caught by the very attractive project assignment, well aware that not many people get the chance or the opportunity to be involved or work with projects like this.
Sammanfattning

Detta examensarbete är en fortsättning av förra årets arbete som bygger vidare på att konstruera en månrover som ska placera ut ett radioteleskop på månens baksida. Projektet görs i samarbete med (JPL) Jet Propulsion Laboratory i Pasadena, Kalifornien.


Projektets slutliga mål är att få bättre förståelse om universums ursprung och dess kontinuerliga förnedring. Detta skulle ge forskarna en möjlighet att studera några av de mest grundläggande frågor som fortfarande väntar på svar.

Vi har tillsammans med en grupp energiingenjörer, Gustav Andersson och Emil Ericsson, tagit del av detta mycket intressanta och speciella projekt som inte många personer i världen har chans eller möjlighet att jobba med. Vi ska i slutet av läsperioden presentera en prototyp som kommer att byggas tillsammans, där vi visar våra moduler och även dess funktion i verkligheten.
1 Introduction
NASA’s future mission uses assets from both NASA’s human and robotic programs to join together both exploration and science work in order to address fundamental questions about the universe. The mission involves an autonomous rover that will be capable of deploying a concept of a radio telescope on the far side of the Moon surface. The radio telescope is known as the most scientifically valuable and technically viable instrument of all instruments proposed for early deployment on the Moon. The lunar telescope is constructed out of a large low frequency lunar array. The lunar array will be created by a large number of antenna stations, constructed out of polyimide film antennas in where dipoles will be the fundamental collecting element. Each antenna station will have a defined number of extended polyimide antenna arms, at the moment a number of 6 arms have been proposed to be appropriate for the task. The polyamide films are found to be flexible enough to be stored in a roll during transportation. The rovers missions is to fetch polyimide films, each 1 m wide and 100 m in length from a Lunar Lander 100 – 1km from the deployment site.

1.1 Background
NASA mission called the Dark Ages Lunar Interferometer is about placing a measuring instrument on the Moon’s far side with the help of an unmanned rover. The measuring instrument is a form of telescope, specially developed for collecting information from the deep universe. Using the instrument will allow better understanding of different phenomena, such as birth of stars, the dark matter and possibly even the universe’s expansion. The far side of the Moon is assumed to be the only place in our solar system that is not affected by interferences from the earth, and the solar radio emissions during the night. The deployment site is depended on a number of factors and parameters such as temperature, surface irregularity and extension of the efficient surface area. These parameters have shortened the list of deployment sites to only three suitable places, all three falling in the category of craters and called Mare Moscoviense, Aiteken and the Tsiolkovsky crater.

1.1.1 Company presentation
This project is carried out in collaboration with NASA and Jet Propulsion Laboratory (JPL), a world-leading manufacturer of space-related products. The headquarters is based in California, USA. NASA’s latest exploration task was a mission to Mars during 2012. The mission was executed with help of a Mars rover named Curiosity.
1.2 Goal and objective
The goal of the thesis is to develop some parts of a robot, a rover that is planned to be used for the far side lunar mission. The rover should be capable of moving around on the lunar surface and overcome the obstacles that may arise from the surface irregularities and the assignment itself. A basic idea for the suspension system has earlier been established by other projects; however the idea was not evaluated and studied further in depth. The objective of this thesis work will be to establish a solution for the suspension system and also to find and establish a solution for the transition stage. A transition stage is originated from the rover transit mode to the action mode. It is a primary stage, necessary for the rover to perform due to the lack of space in the rocket that will ship the rover to the moon.

1.2.1 Problem formulation
For the necessary task, derived from rolling out the rolls of polyamide antennas on lunar surface, a rover has to be designed that will be able to operate and get around smoothly. Difficulties in the task may arise from the obstructions of the lunar environment, from cosmic radiation, large temperature fluctuations and the lack of atmosphere which already at this stage excludes any cooling of systems by airflow. Another problem may occur when placing the antenna roll, while the weight varies in the antenna roll, it can affect negative on the stability system of the rover if the system is not properly designed.

1.3 Limitations
This work will to some extend be executed in a collaboration with thesis working students from energy engineering. The complete work has been divided into two projects where students from energy engineering will focus on the development of the motors, solar panels, batteries and the general power supply. The areas that will be the focus of this thesis work are the suspension system, including connection to the chassis and the transition system from the standby mode during transportation and the ready mode when ready for action. Furthermore, balancing of the chassis while the rover is operating will also be a part of this thesis work. The depth of the work will be set to the detail level.

Due to the lack of time, other areas such as the steering and the steering system, motor and gearing, framework/chassis and wheels will not be within the scope of this thesis work.
2 Method

In this case, constructing a new part of the suspension, the decision was made to work within the embodiment design of construction by (Freddy Olsson, 1995) as a method which we are familiar and use to working with. The reason that working with conceptual design is remaining even this year is that fundamental parts in the embodiment design of the suspension that we find in last year’s results seems to be missing (Dark Ages Lunar Interferometer (DALI): Deployment-Rover, (Mobility System, Chassis, Deployment mechanism), (E. Andersson; P-J. Bengtsson; T. Johannesson; K. Hansson;, T. Stanimirovic;, J. Winberg, , 2013). When this project which includes designing of suspension at principle level is finished, the remaining work is suitable for further studies in detail design.

2.1 Method discussion

Different methods that exist in embodiment design are compared to each other (Freddy Olsson, 1995), Total Design (Stuart Pugh, 1991) and Product Design and Development (Karl Urlich, Steven D. Eppinger, 2011) and a quite similar methodology is described and presented in these books. (Freddy Olsson, 1995) have more concrete examples of different stages in design that have to be made for a successful construction. Due to that and also from earlier experience with similar projects according to this philosophy, we choose to simply follow these methods basic and relevant parts.

2.2 Methodology

Embodiment design that stands for a development and assumes appropriate solution to the problem, find its way through different methods to a principle solution to the problem. Embodiment design stands for a development which assumes an appropriate solution to the problem, finds its way through different methods to a principle solution to its ultimate goal. The embodiment design is performed in few steps:

- Product definition.
  The product definition covers multiple areas. These are; field of application, main assignment, environment, human impacts and possibly, the economic conditions. The product definition will not be described in this thesis work due to the reason that it already has been described in previous works which in this work only would be recognized as a repetitive content.

- Product research and criterion
Product research has been made to some extent on earlier thesis works that were related to the rover, but it has also been made on the research level through scientific journals about earlier rovers. Some criteria that were found to be relevant from last year’s thesis work will together with a number of new suitable requirements and desires be incorporated and evaluated in this work.

- **Development of product proposals**
  For generating product proposals, brainstorming will mainly be used as the method for obtaining different proposals. When brainstorming is used in an early stage of a project, it is important to be open minded and to accept all suggestions. One should have the assumption that there are no bad ideas and the mentioned proposals should not be criticized. The reason for this is that many an idea may seem to be too complicated, or not relevant in the beginning, but when further evaluated it may prove that the idea was a good one after all. In this stage of the project, the quantity of ideas was considered to be important as quantity often generates later on to a qualitative proposal. The ideas were subsequently further developed, finalized and described in more detail.

- **Evaluation of product proposals**
  In this stage the product proposals are evaluated against the established criteria. The different product proposals advantages, disadvantages, strengths, weaknesses and deficiencies against the lined-up requirements will in this stage be shown. The evaluation process can be made on some different levels and applied by various methods. With the help of evaluations that will be made, the most appropriate proposal will subsequently be used for further work.

- **Presentation of a selected product**
  The selected product proposal is often presented in freehanded drawings or as physical models. Since proposal is in its basic element some additions may occur if that seems to be needed for products further development. Finally should product proposals meet all requirements and match previously established preferences. In the presentation of selected product pros and cons are presented and even technical and economic aspects are noted.
3 Theoretical frame of reference

Theoretical research on the present and past studies is a necessary stage to perform in order to gain a better understanding of the project framework and the areas involved. A good understanding of the different areas and parameters will consequently be of great help when the stage of generating ideas comes to question. Therefore, the following subchapters are presenting studies of the lunar environment, characteristics of the lunar surface and some noteworthy parts of the rover for this work.

3.1 Lunar landscape

The terrain of the moon can be divided into highlands and lowlands. The difference in altitude lies between approximately 10 000 m in the highland and around -9 000 m in the depths, which is quite similar to the one on earth. But the geology is anyway very different. The moon does not have an atmosphere. That makes it exposed to meteor impacts, but it also eliminates erosion due to water. A long time ago the moon was volcanic active, and it is volcanism and meteor impacts that have formed the lunar landscape. This makes the lunar surface mainly very rough, but there are also some smoother areas.

There are some darker areas of the moon which represent lowlands. These are called lunar maria (latin for seas). There are however no seas, and have ever been, on the moon, but the early astronomers thought that, and therefore it is still called lunar maria or seas. Most of the lunar marias is located on the close side of the moon. Less than one percent of the far side of the moon is covered by lunar maria. The lunar marias consist of a relatively flat area compared to the surrounding areas, because these areas are much younger. (figure 3.1-1) These areas are made from volcanic activity, and the dark areas consist of solidified lava.

Figure 3.1-1 flat mare (dark area) in Tsiolkovsky crater surrounded by rough terrain (NASA, 1968)
3.2 Lunar surface material
The material which covers the moon’s surface is called regolith. It consists of broken rock, soil, dust particles and other related materials. Regolith can also be found on earth, mars and other terrestrial planets, but each one has its own specific properties. The regolith on the moon consists of a composition of oxygen, silicon, iron, calcium, aluminum, magnesium and other materials in smaller concentrations. The regolith represents/makes up a quite compact soil with a fine and powdery texture. It is able to support a wide variety of roving vehicles according to Lunar sourcebook: A users guide to the moon (Grant H. Heiken, David T. Vaniman och Bevan M. French(eds.), 1991), It has a density of about 1.5 g/cm³.

![Figure 3.2-1: Footprint in regolith taken on the Apollo 11 Mission (NASA, 1969)](image)

3.3 Radiation
The moon has no protection from radiation like earth has. The strong magnetic field and the thick atmosphere protect earth from a wide range of the radiation from space. There are mainly three types of radiation on the moon: solar cosmic rays, solar wind and galactic cosmic rays. These radiations consist of protons and electrons with extremely high energy. The penetration can vary from micrometers to meters depending on their energy and composition (Heiken et al., 1991, p.47).

3.4 Moons potential
National Aeronautics and Space Administration (NASA) plans to return humans to the Moon. It may be the place where astronauts are preparing for upcoming journeys to Mars but it is also an established place for the scientific investigations that will be made on the deep universe. The moon is potentially the only site in the inner solar system for special scientific investigations like the ones that will
emerge with the use of ROLLS instrument. There are several reasons found to be 
the source for this statement, noted and shortly presented in this subchapter.

No human generated interference: Means that the relevant frequencies used by 
both civil and military communication transmitters may interfere in the range of 
Dark Ages frequencies as well. Those signals are much stronger than the HI 
signals and detectable even at remote locations above the Earth. However, lunar 
far side is protected by the Moon itself which consequently is reducing such 
interferences to a more negligible level (Alexander & Kaiser 1976).

No (Permanent) Ionosphere: Ionosphere produced by the Earth is limiting radio 
observation that simply is reflecting interference from distant transmitters. On the 
Moon those errors are occurring only during the day time due to the solar 
irradiation that ionized plasma layer witch disappears during the night.

Shielding from Solar Radio Emissions; the Sun is the strongest celestial source at 
the frequencies when it is bursting. The physical shielding is the only way to 
mitigate solar radiation effect within our solar system. Such shielding is possible 
by observation during lunar night at a point when the moon is physically 
protecting the surface.

3.5 Previous mobility system designs
In order to create a better understanding of the planetary environments in our 
Solar system, explorations on planetary basis are necessary for the scientific 
research. Prior to sending a robot for scientific research on a planetary surface, 
background studies should be made on the robots and the devices that have been 
used for similar kind of missions. The experience with the previous robots ought 
to be analyzed and considered for the upcoming missions. However, a chance for 
new ideas and different solutions should be given for development purposes of the 
robots and for increasing the chances of success for future missions.

Up to now, every scientific research on a planetary surface was executed with a 
multi-wheeled rover. In order to have successful missions even in rough 
environments such as Mars mountain cliffs or low gravitational places such as 
esteroids and comets, other mobility solutions should be considered. Also robots 
with multiple capabilities such as drilling, digging, lifting etc. should also be 
considered for development purposes in order to be able to extract even better 
information from the surfaces and environments.

In the following background research, past and current designs of mobility 
systems developed for planetary explorations at JPL are presented. Some of robots 
have been used for different missions and some have been used as prototype
models for test purposes. Multi-wheeled mobility system is discussed and compared with alternative mobility designs such as legged or hopping systems. The different designs described in the background research are only brought up for the inspirational purposes of the given thesis assignment and for better understanding of questions like, what can be expected of a robot and what kind of job the robots are put to. The research summarizes main features of mobility designs that exist today and some of the experimental test results. Conclusions and ideas that are extracted from this chapter may have a great influence in further work.

3.5.1 Sojourner

Mission
The first unmanned rover successfully landed on another planet after a seven months long journey. Mission was designed to demonstrate the technology necessary to deliver a lander and free ranging rover to the surface of Mars in a cost-effective and efficient manner. It explored the vicinity of the lander, probing the Martian surface while getting pictures of rocks and the way they are arranged. It analyzed the chemical mixture of soil and the various rocks, dug into and measured the soil strength and the abrasive characteristics.

From landing until the final data transmission on September 27, 1997, Mars Pathfinder returned 2.3 billion bits of information, including more than 16,500 images from the lander and 550 images from the rover, as well as more than 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors. Findings from the investigations carried out by scientific instruments on both the lander and the rover suggest that Mars was at one time in its past warm and wet, with water existing in its liquid state and a thicker atmosphere.

Technical data
Describing briefly functionality and capability of planetary rover Sojourner is that it has six wheels, each 130 mm in diameter and made of aluminum with stainless-steel treads and cleats. A rocker-bogey suspension system allows each wheel to move up and down independently of all the others. Because of its mobility design is rover is capable of clamming a rock of more than 200 mm height.

A laser system in combination with multiple monocular cameras is used to detect obstacles in front of the rover and help it choose the best way forward. The vehicle is steered autonomously to avoid obstacles while continuing to attempt to achieve the commanded goal location. Tilt sensors allow the rover to be autonomously halted if it is dangerously close to tipping over. While stopped, the
rover updates its measurement of distance traveled and heading using the averaged wheel odometry to calculate its location. This provides an estimate of progress to its goal. The lander is also a crucial element, for the navigation of the rover. Its stereo cameras obtain panoramic images of the area surrounding the rover which allows mission operators on Earth to periodically locate the rover as well as determine way for following rover movements. As a consequence, rover operations are limited to the near vicinity of the lander.

3.5.2 The Rocky 7 rover

Mission
After its initial construction, Rocky 7 was used for desert field tests in 1996 and 1997. Following that, it was used for several years of development and testing, including rock grasping, and wheel-terrain contact estimation techniques. From 2001 onward, it has been a test bed for new software development. More recently it has been considered a likely candidate for rover studies for Mars Sample Return technology development. In recent years, Rocky 7 has undergone major upgrades of its electronics which is comparable to flight systems planned for upcoming rover missions.

Technical data
Rocky 7 was originally built as a next-generation design to follow Sojourner (Next Generation Mars Rover Prototype (R. Volpe; J. Balaram; T. Ohm; R. Ivlev, 1997). It is approximately the same size but was given capabilities similar to its much larger predecessors to demonstrate the capabilities of leaderless operation. First, a much faster computer system was used, enabling onboard stereo processing. Second, the deployable stereo camera mast provided imagery of the surrounding terrain from human-eye height, like the Pathfinder Lander that was used in Sojourner mission. Third, the Sojourner inertial sensor system was supplemented with a wide-field-of-view sun sensor that helped maintain absolute
heading measurements not possible otherwise. Fourth, the manipulation system enabled terrain sampling and multiple science-instrument placements.
It is approximately 600 x 400 x 250 mm in size and 16 kg in mass. The mobility system uses a variant of the rocker-bogie mechanism found on most JPL rovers. On Rocky 7, only the front wheels are steerable, while the back bogie wheels are close together and have no steering. This mobility design concept was implemented to test the maneuverability of a system with fewer actuators. These actuators were instead used in a short sampling manipulator that is stored across one end of the vehicle, and a long instrument manipulator (mast) that is stored through a slot in the solar panel. The deployed mast holds the navigation cameras at 1.4 m above ground level, providing higher-vantage-point viewing for operators or onboard algorithms.

3.5.3 The LEMUR robots (I, II a, II b)

Mission
The assembly, inspection, and maintenance requirements of permanent installations in space demand robots that provide a high level of operational
flexibility relative to mass and volume. Such demands point to robots that are handy, have significant processing and sensing capabilities, and can be easily reconfigured to both physically and algorithmically tasks. The LEMURs (Limbed Excursion Mechanical Utility Robots) are designed to address these challenges ([*Ground Mobility Systems for Planetary Exploration - Legged & hopping rovers*](P. Fiorini, 2000).

LEMUR is a small, agile and capable six-legged walking robot that has been built at the Jet Propulsion Laboratory to perform dexterous small-scale assembly, inspection and maintenance of macro space facilities. It is intended to expand the operational envelope of robots in its size class (sub-5kg) through the flexible use of its limbs and effectors, as well as through the modular change out of those effectors.

**Technical data**

Evolving from Lemur I, Lemur IIa is an extremely capable system that both explores mechanical-design elements and provides an infrastructure for the development such as force control for mobility and manipulation, and adaptive visual feedback. Actual Lemur II system summary is that rover mass as 9 kg and have 6 limbs that have 24 degrees of freedom. The physical layout of the system consists of six 4-degree-of-freedom limbs arranged axi-symmetrically about a hexagonal body platform. These limbs incorporate a "quick-connect" end-effector feature below the distal joint that allows the rapid change-out of any of its tools. The other major subsystem is a stereo camera set that travels along a ring track, allowing much better surroundings vision. The current Lemur IIa platform represents the jumping-off point toward two more-advanced robotic platforms that will support NASA's Vision for Space Exploration.

Lemur IIb is designed build as a 4-limbed robotic system that is being used to investigate several aspects of climbing-system design, including the mechanical system (novel end-effectors, kinematics, joint design), sensing (force, attitude, vision), low-level control (force-control for tactile sensing and stability management), and planning (joint trajectories for stability). The technologies developed on this platform will be used to build an advanced system that will climb slopes up to and including vertical faces and overhangs while reacting to forces to maintain stability and do useful work that may be placement of sample acquisition/instrument. Among the most advanced of these technologies is a new class of Ultrasonic/Sonic Driller/Corer (USDC) end-effectors capable of creating "holds" in rock and soil as well as sampling substrates.
3.5.4 ATHLETE

Mission
In the beginning of Year 2020 the National Aeronautics and Space Administration (NASA) plans to return humans to the moon in an effort to build a permanent lunar outpost. Astronauts will use the moon’s natural resources to conduct scientific investigations and prepare for a journey to Mars. Prior to human arrival, NASA plans to conduct robotic precursor missions for landing site reconnaissance, analysis of the natural resources, and technology risk reduction for the human lander. The All–Terrain Hex–Limbed Extra–Terrestrial Explorer (ATHLETE) was designed to aid in both the manned and unmanned portions of the return to the moon by providing versatile mobility and manipulation capabilities to be used via both remote operations from the earth and in cooperation with astronauts on the lunar surface.
The ATHLETE Explorer is a complex robot with more degrees of freedom than any other planetary rover (*Mobility and manipulation system for the moon ATHLETE* (Wilcox, Brian H. 2007)). New mobility platform developed for potential lunar operations. The rover can traverse terrain that no other planetary rover can traverse. This six limbed rover is designed to navigate quickly over benign terrain by rolling, traverse rough and steep terrain by walking, as well as perform general manipulation of tools and payloads. This flexible robotic platform will provide a mobile base for pressurized lunar habitats allowing for long range surface exploration and crew transport. This wheel on-limb rover is highly adaptable and will potentially play a key role in man’s return to the surface of the moon. It can act as an exploration rover, a crew transport vehicle, and a construction asset on the surface of the moon. It will also insure construction of lunar assets providing astronauts with the ability to assemble, maintain, and service a wide range of cargo.

**Technical data**

This robot was designed as a prototype vehicle to test the wheel–on–limb mobility concept. The 850 kg ATHLETE vehicle is designed with an open hexagonal frame, as shown in Figure 3.5.4-4, which measures 2.75 m tip to tip that with a six degree of freedom limb located at each vertex of the hexagon. Each of these limbs is identical to reduce complexity of design. The end of each limb is a powered wheel which can be used on gentle terrain to drive at speeds up to 10 km/h. On rough and steep terrain the wheel can be locked allowing the vehicle to walk. The 36 joints share several common design elements. To reduce even the overall vehicle complexity, identical actuators are used as the first stage to all of the joints. It can negotiate a step nearly equal to its fully extended limb length and more than three times its wheel diameter.
Theoretical frame of reference
4 Results
In the following chapter, results and conclusions that have been established during
the work are presented and explained. Since the work has been done on two
different sub constructions, results are divided into suspension principle and
transition mechanism.

4.1 Criteria
By brainstorming together with our mentor we came up with some requirements
and wishes, shown in table 4.1-1. These notes will be the basis for the evaluation
and the selection stage. Some of the relevant criteria are taken from last year’s
project.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Wishes</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Be able to drive over obstacles on one side without affecting the other.</td>
<td>W1 Reliable</td>
</tr>
<tr>
<td>R2 Capable of driving in angular slopes up to 30 degrees in any direction.</td>
<td>W2 Stable during driving</td>
</tr>
<tr>
<td>R3 Able to continue mission even if some component fails.</td>
<td>W3 Simple construction/design</td>
</tr>
<tr>
<td>R4 Able to clear obstacles as big as wheel diameter or smaller.</td>
<td>W4 Simple transition between driving and transport mode.</td>
</tr>
<tr>
<td>R5 Robust construction. Withstand 20 G-forces.</td>
<td>W5 Lightweight design</td>
</tr>
<tr>
<td>R6 Have a driving and transport mode.</td>
<td>W6 Good terrain mobility</td>
</tr>
<tr>
<td>R7 Withstand the low and high temperature on the moon.</td>
<td>W7 Design mobility system to be compatible with chassis of different designs without loss of functionality</td>
</tr>
<tr>
<td>R8 Cables must withstand radiation.</td>
<td></td>
</tr>
<tr>
<td>R9 Fit into the transport capsule.</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1-1, criteria

4.1.1 Explanation of the criteria

- R1: Be able to drive over obstacles on one side without affecting the other.
Maintain the chassis as stable as possible, so that the deployment of the antennas is performed smoothly. The wheels must perform independently.

- R2: Capable of driving in angular slopes up to 30 degrees in any direction. Good balance. The rover has to stay stable both during transport and during load. The center of gravity shall be centered.

- R3: Able to continue mission even if some component fails. Good redundancy and margin of error. If something fails the rover has to be able to continue and finish the mission anyway. The chance for error has to be minimal. Even if an error occurs it shall not be devastating for the mission.

- R4: Able to clear obstacles as big as wheel diameter or smaller. We assume that the deployment site at the lunar surface is smooth, but there is a chance for unsuspected obstacles, which the rover must be prepared to clear.

- R5: Robust construction. Withstand 20 G-forces. The construction is not allowed to break apart during transport to the moon. Be able to withstand unsuspected situations like for example if something falls onto the rover during transport or unloading from spacecraft.

- R6: Driving and transport mode. The rover must be folded when transported because of the lack of space in the spacecraft and it has to be automatically unfolded when arriving to the moon.

- R7: Withstand the low and high temperature. There is a big difference in temperature on the lunar surface between the day and night. The rover needs to withstand both the very hot and very cold environment as -233 degrees Celsius and 123 degrees Celsius.

- R8: Cables must withstand radiation. Safe cable placement. The cables have to be placed so that they are as safe from failure as possible.

- R9: Fit into transport capsule. Because there are many things that will be sent in the capsule, and there is
limited space, the rover cannot be too big to fit into the transport capsule. The space must be considered.

- W1: Reliable
  Operate reliably and have a reliable construction.

- W2: Stable during driving
  The chassis shall be affected as little as possible by movements and obstacles to provide a smooth deployment of the antennas.

- W3: Simple construction/design
  The construction should have as simple design to maintain a good redundancy. Less moving parts mean that there are fewer things that can fail.

- W4: Simple transition between driving and transport mode.
  If the transition is advanced, there are more things that can fail.

- W5: Lightweight design
  It costs a lot of money to send a certain mass to the moon, therefore a low mass is desired. And a lower density causes lower strain during the 20 g-forces period.

- W6: Good terrain mobility.
  Clear obstacles and irregularities as well as possible.

- W7: Design mobility system to be compatible with chassis of different designs without loss of functionality
4.2 Comparative weight table

**Explanatory**

Compare the horizontal with the vertical criteria. If the horizontal is more important than the vertical, it gets 2 points. If the vertical is more important than the horizontal, the horizontal gets 0 points. If both are equally important it gets 1 point.

<table>
<thead>
<tr>
<th>Wishes</th>
<th>Reliable</th>
<th>Stable during driving</th>
<th>Simple construction/design</th>
<th>Simple transition between driving and transport mode.</th>
<th>Lightweight design</th>
<th>Good terrain mobility</th>
<th>Design mobility system to be compatible with chassis of different designs without loss of functionality</th>
<th>Points</th>
<th>Weight (=Points /Total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliable</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>8</td>
<td>0,190476</td>
<td></td>
</tr>
<tr>
<td>Stable during driving</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>8</td>
<td>0,190476</td>
<td></td>
</tr>
<tr>
<td>Simple construction/design</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>0,095238</td>
<td></td>
</tr>
<tr>
<td>Simple transition between driving and transport mode.</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>7</td>
<td>0,166667</td>
<td></td>
</tr>
<tr>
<td>Lightweight design</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>0,071429</td>
<td></td>
</tr>
<tr>
<td>Good terrain mobility</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>11</td>
<td>0,261905</td>
<td></td>
</tr>
<tr>
<td>Design mobility system to be compatible with chassis of different designs without loss of functionality</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0,02381</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.2 Comparative weight table**

I this case we choose to use the “points” as weight instead of the numbers in “weight”. It doesn’t matter in this case, because it is just the proportion between the numbers which important. It will become more exact and understandable.
4.3 First evaluation: Suspension principle
To get good connection and balance between the suspension and the chassis, we came up with a few concept ideas. The concepts are going to be evaluated with a concept selection table. Consider is taken to the criteria we have set up. All the requirements must be fulfilled and then the concepts will be even evaluated to the wishes. The different concepts are presented in appendix 1. To our help with ideas and to see already functioning models we took use of some articles like (The Challenges of Designing the Rocker-Bogie Suspension for the Mars Exploration Rover (Harrington, Brian D.; Voorhees, Chris 2004)) and (Comparison of Past, Present and Future Rover Systems (Wilson, Gregory R.; J. M. Andringa; L. W Beegle; J. F Jordan,; G. S.; Mungus, D Muliere,; J. Vozoff,; T. J. Wilson, 2005)

4.3.1 Concept definition and basic evaluation
In this section the different concepts are described. Weaknesses and strengths are presented as well.

S1. Concept S1 has a rocker boggy suspension, as the last year group has figured out. All the joints in the suspension can move freely. It is attached to the chassis through a slot, and the position in this slot is controlled by electronics back and forth to compensate the weight of the antenna roll and balance the chassis while driving so that the center of gravity stays in the right position.

This concept should move very easily over obstacles and surface irregularities, but it can have a tendency to sway forth and back caused by speed changes when driving over obstacles. Another weakness is that the balancing system not is perfectly reliable and that it would take a big place in the chassis. It needs a bigger and more advanced system to control the rover, which would lead to a higher weight.

S2. Concept S2 is based on the first one, but instead of having the suspension moving along the chassis, there is a weight inside the chassis that moves back and forth to balance the chassis. The weight can for instance consist of batteries or electronics that already is needed inside the chassis rather than adding something extra for this purpose.
This concept has about the same advantages and disadvantages as concept S1. It has good terrain mobility but is not very reliable because there are more parts that can fail.

S3. Concept S3, that also have a kind of rocker boggy suspension, has one moving and one ridged axle that is attached to the chassis, and therefore doesn’t need to have any system for balancing the chassis.

This concept will be stable as long as it stays on fairly flat ground. But if some obstacle appears it will be difficult to handle. For example, if a bigger stone appears only on one side of the rover and it tries to drive over it, the other side wheel will be “hanging in the air”.

S4. Concept S4 is based on concept S3, but it has one freely moving joint and one that can move and is controlled by a spring. The movement of the spring is constrained to a certain angle and after that angle it turns to rigid axle.

The spring allows more movement and gives the concept better terrain mobility. It will manage smaller obstacles much better than concept 3, but it still could have problem with obstacles larger than the wheel diameter.

S5. Concept S5 has a rocker boggy suspension with only freely moving axles. The axle which is attached to the chassis is located high up on the chassis so that it can freely hang underneath and stabilize itself by gravity.

When the rover has to pick up an antenna roll, it has a system that locks its axle so it stays stable even when the center of gravity is not centered under the joint between the chassis and the suspension. The antenna roll is deployed from the middle underneath the chassis. In that way the center of gravity always stays in a right position.

S6. Concept S6 to think a little bit outside the box we have thought about a new suspension concept with eight wheels instead of six. This concept will have better balance possibilities. It is simple and does not need any extra components for stabilizing or balancing. The suspension is easy to adapt to
different ride heights. The suspension arms will be fastened in freely moving joints.

This concept will have okay terrain mobility, but not as well as some of the others and it will conflict with the last years students work. Because it may have 8 wheels steering, it will have more details to consider.

S7. Concept S7 is based on the concept above. The difference is that this one also has a spring joint which will improve the terrain mobility by increasing the possible movement of the wheels, but it will also result in a little bit worse overall stability.

S8. Concept S8 has a differential in the middle, which balance up the chassis. It allows the left and right sides to work independently which improves stability and terrain mobility. The chassis is less affected if wheels are traveling over obstacles.

A disadvantage with this concept is that the differential itself will take much space in the chassis. This could be difficult if many things have to be placed inside the chassis later. If the weight distribution is not properly balanced, for instance if the rover lifts a heavy object, the different wheels will have different pressures on them.

S9. Concept S9 has a construction that works like a differential, but is done differently. It has a freely moving beam that is fastened with the cassis, and then freely moving beams connected with suspension. It could be placed on top of the chassis or underneath, allowing other things to be mounted on the top of the rover.

This concept has more moving parts, but because everything is working mechanically and is not depending of any electronics. Due to that this concept can be considered as reliable.
4.3.2 Table over fulfilled requirements

To be able to continue to evaluate the different concepts against wishes we first have to see if they really match up to all the requirements we have. We are going to do that by comparing the requirements with 9 different concepts that we have developed earlier. If concept does not fulfill the requirements it will not be taken to the next step.

In table 4.3.2-1 we check if the concepts fulfill all the requirements which are essential.

Explanatory:
X = Requirement fulfilled
O = Requirement is not fulfilled
/ = Requirement is not relevant in this section

<table>
<thead>
<tr>
<th>Requirements</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Be able to drive over obstacles on one side without affecting the other.</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>R2: Capable of driving in angular slopes up to 30 degrees in any direction.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>R3: Able continue mission even if some component fails.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>R4: Able to clear obstacles as big as wheel diameter or smaller.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>R5: Robust construction. Withstand 20 G-forces.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>R6: Have a driving and transport mode.</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>R7: Withstand the low and high temperature on the moon.</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>R8: Cables must withstand radiation.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Does concept fullfill all the requirements? YES YES NO YES YES YES YES YES YES

By doing this table we can see that concept S3 does not fulfill all the requirements. Due to that it will not be taken further to the next step. The rest of the concepts will be evaluated further with a concept selection table.
### 4.3.3 Concept selection table

In table 4.3.3-1 we evaluate the different concepts considering the wishes. We choose to go further with the best concept to the next step which will be how to make the transition between transport and driving mode.

W4 is not considered in this table because it is not relevant in this section. We are later going to evaluate some concepts/models of the transition between transport and driving mode.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>S1</th>
<th>S2</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>G</td>
<td>P</td>
<td>G</td>
<td>P</td>
<td>G</td>
<td>P</td>
<td>G</td>
<td>P</td>
</tr>
<tr>
<td>W1 Reliable</td>
<td>8</td>
<td>2</td>
<td>16</td>
<td>8</td>
<td>2</td>
<td>16</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>W2 Stable during driving</td>
<td>8</td>
<td>3</td>
<td>24</td>
<td>2</td>
<td>16</td>
<td>4</td>
<td>32</td>
<td>3</td>
</tr>
<tr>
<td>W3 Simple construction/design</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>16</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>W4 Simple transition between driving</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>and transport mode.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W5 Lightweight design</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>W6 Good terrain mobility</td>
<td>11</td>
<td>4</td>
<td>44</td>
<td>3</td>
<td>33</td>
<td>2</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>W7 Compatible to fit if chassis</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>design changes without changed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>properties</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total points</td>
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<td>65</td>
<td>101</td>
<td>117</td>
<td>121</td>
<td>109</td>
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<td>144</td>
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<tr>
<td>Rank</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Continuing with</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Table 4.3.3-1: Concept selection table**

### 4.3.4 Summary of evaluation 1

Concept S9 presents a type of differential that allows independent operation and movement of the suspension on both sides of the rover has been tested and proved to be the best of all the above mentioned concepts. S9 met all requirements and have proved it to be most suitable when it comes to the wishes that have been established. With the help of evaluations, S9 was chosen to be presented as a possible solution to final part of suspensions that stabilized chassis. Since it still is a fundamental solution, some changes or adjustments at a size or position of details can occur in order to achieve the best possible result in the future. S9 properties will be taken into account while developing new concept for transitions mechanism to get a concepts that work well together.
4.4 Second evaluation: Transition mechanism

Transition between driving and transport mode has to be done smoothly and reliably. Some concept ideas have been produced considering that and are going to be evaluated in this section.

Consider is taken to the criteria we have set up. All the requirements must be fulfilled and then the concepts will be even evaluated to the wishes. The different concepts are presented in appendix 2.

4.4.1 Concept definition and basic evaluation

In this section the different concepts are described.

T1. Concept T1 is a simple mechanical solution with a leaf spring that holds up the whole chassis. The spring will be adjusted to hold the weight of the rover on the moon but not on the earth. On earth it will be in transport mode all the time due to the earth gravity, but when it comes to the moon it will automatically be in driving mode because the moon gravity is much smaller. The springs force is always the same regardless to where it is.

To make it even more reliable there can be any kind of locking mechanism that holds the suspension in place during transport which releases when the rover comes to the moon. This eliminates the risk of unpredictable problems during transport in capsule.

T2. In concept T2, the suspension arms of the rocker boggy are separated into two different pieces which can rotate freely from one another. They are both attached to cog wheels which are driven by one (or two, for higher redundancy) motor each. The mounting for the motors is also able to rotate freely and is attached to the mechanism that allows the suspension to move independently. The motors change the angles of the suspension arms so it can go from transport mode to driving mode.

T3. Concept T3 has a cylinder which can go in and out, like a hydraulic one. But a hydraulic system would probably not work on the moon, no either get room in the rover. Instead it could be a cylinder driven by
Results

electromagnetism or a threaded rod.
The cylinder changes the angles of the suspension arms so it can go from transport mode to driving mode.

T4. Concept T4 has a motor driven rod which can change its angle and is attached to one rod connected to each of the suspension arms, moving them from transport mode to driving mode.

T5. In concept T5 the suspension arms can rotate freely from one another. Each of them has cogs and is connected with one cog wheel each. These cog wheels are also connected to each other which causes the two suspension arms rotate in different directions. One of the cog wheels is connected to a motor which drives the mechanism form transport mode into driving mode.

T6. Concept T6 is an easy transition between transport and driving mode that is motorized. It acts so that the chassis height is regulated in a vertical slot. Height will depend on required transportation or driving mode. In transport mode the suspension is in the highest position in the slot so that the wheels are leveled to the chassis bottom. When going into driving mode the suspension is at a lower position in the slot, raising the chassis from the ground.

This concepts weakness is that the transition system not is perfectly reliable and that it would take a big place in the chassis. It needs a bigger and more advanced system to control the rover, which would lead to a higher weight.
In concept T7 the suspension arms do not rotate around the same axle. Both of them have cogs. There is a rod with cogs that can go up and down, driven by a cog wheel on a motor, causing the suspension arms to change their angles, which turns the rover from transport mode into driving mode.

Alternatively there could be a wheel with cogs on the sides rotating instead of having the rod going up and down.
4.4.2 Table over fulfilled requirements

In the previous evaluation matrix, we took most of the requirements into account but there were two that were irrelevant to that particular evaluation. We will take these two together with the others requirements into the following matrix and exclude the ones that are not relevant. We have the same evaluation rating as in the first evaluation.

Explanatory:
X = Requirement fulfilled
O = Requirement is not fulfilled
/= Requirement is not relevant in this section

<table>
<thead>
<tr>
<th>Requirements</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Be able to drive over obstacles on one side without affecting the other.</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>R2: Capable of driving in angular slopes up to 30 degrees in any direction.</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>R3: Able continue mission even if some component fails.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>R4: Able to clear obstacles as big as wheel diameter or smaller.</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>R5: Robust construction. Withstand 20 G-forces.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>R6: Have a driving and transport mode.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>R7: Withstand the low and high temperature on the moon.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>R8: Cables must withstand radiation.</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Does concept fullfill all the requirements? YES YES YES YES YES YES YES

Table 4.4.2-1: Table over fulfilled requirements

Table 4.4.2-1 ensures that all requirements are fulfilled and that they can be taken to the next step.
4.4.3 Concept selection table

In table 4.4.3-1 down below we evaluate the different concepts considering the wishes. We choose to go further with the best concept.

W2 and W6 are not considered in this table because they are not relevant in this section. Even W4 is excluded because the transition was already decided how it should be by the previous group. All the solutions are mainly working in the same way, and have only two modes. It is also because the requirement in this case gets the same meaning as W3.

Table 4.4.3-1: Concept selection table

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>G</th>
<th>P</th>
<th>G</th>
<th>P</th>
<th>G</th>
<th>P</th>
<th>G</th>
<th>P</th>
<th>G</th>
<th>P</th>
<th>G</th>
<th>P</th>
<th>G</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Reliable</td>
<td>8</td>
<td>5</td>
<td>40</td>
<td>4</td>
<td>32</td>
<td>3</td>
<td>24</td>
<td>4</td>
<td>32</td>
<td>4</td>
<td>32</td>
<td>3</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>W2</td>
<td>Stable during driving</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W3</td>
<td>Simple construction/design</td>
<td>4</td>
<td>5</td>
<td>20</td>
<td>4</td>
<td>16</td>
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<td>20</td>
<td>4</td>
<td>16</td>
<td>4</td>
<td>16</td>
<td>2</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>W4</td>
<td>Simple transition between driving and transport mode</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W5</td>
<td>Lightweight design</td>
<td>3</td>
<td>5</td>
<td>15</td>
<td>3</td>
<td>9</td>
<td>4</td>
<td>12</td>
<td>4</td>
<td>12</td>
<td>4</td>
<td>12</td>
<td>2</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>W6</td>
<td>Good terrain mobility</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W7</td>
<td>Compatible to fit if chassis design changes without changed properties</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>5</td>
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<td>7</td>
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<tr>
<td>Continuing with</td>
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<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
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</tr>
</tbody>
</table>

4.4.4 Summary of evaluation 2

It is easy to decide which concept to go further with. Concept T1 has a superior amount of points. If the result for concept T1 would not have been so superior and been more like in T2, T3, T4 and T5 it would have been more difficult to decide which is the best, because they are so even. Then it would be needed to look closer at more details to do the evaluation and maybe even need to come up with new criteria. T1 is a simple mechanical solution with a leaf spring that on behalf of different force of gravity due different tasks. With this mechanical solution we eliminate the risk of failing due to electrical or electronic failure.
5 Discussion
Since this is a project in the early stages, one should think of that the results that have been established at this time may and will most likely alter. The extent of the project is unfortunately not yet fully defined nor has the exact procedure of the rover been precisely set. The long time before launch will in some cases create requests for some concepts and solutions to be reconsidered or completely redrawn. Nevertheless, the technology is advancing by each day and doing it so rapidly, meaning that it may be a whole lot easier in the future to find new solutions to a range of different problems. Either way, we are pleased with what we have achieved since all this should have minor effects on our results. In view of the fact that the established results in this thesis work are not directly covered by the advancement of the technology, but of mechanical designs that always strive for simple solutions.

In the beginning of the project we put a lot of time on finding out and making proper estimations on the weight of antenna rolls. We found it to be an important parameter that should be considered in order to be able to achieve proper balance of the rover. The later research of earlier works showed that the weight of the antenna rolls would be in the range of 15-75kg, making it insignificant for the balancing system. The time consumed for this research made us fall behind in our schedules, which lead to that our thesis plan needed to be rewritten. This is a noteworthy point for future work; one should always leave room for any risks or necessary changes that may arise. Nevertheless, knowing that the weight did not affect so strongly on the rover and given more time for the thesis work, an alternative solution to the design of the rover antenna transportation system, could be evaluated. Instead of loading only one antenna roll at the time, the total roving distance could be far shorter if the rover had the capability of transporting several rolls at once, in such way reducing the traveling distance. For instance, the rover could carry a cassette with all the antennas ready, or the base station could have the antennas preinstalled waiting to be picked up and rolled out.

The results can also always be further refined. For example, more solutions for the balancing system could be developed. One could evaluate whether it is the best solution to have the balancing system (se figure 6.1-2 in the next section) on the top of the chassis. It could be studied whether it would be better to have it on the inside of the chassis or on the underside, or even other places.

There is also room for refining of the spring. It could be studied whether any other type of spring would be more suitable and if so, how it would be arranged.
Even the red joints (see figure 6.1-2 in the next section) could be changed to ball joints, for example.

These are examples of things that can be refined, there can even be found out more things.
6 Conclusions

To be part of a project as this one has been really exciting from day one. And it would be even more exciting to be able to help develop it all the way to the finish, but given the time limits we had, we are still very pleased with the results we have achieved. Now that we are approaching the end, we are having more question and many new ideas and recommendations on future work.

Since we would construct two details on the rover, goal was not just to have two good concepts but also two that are designed so that they are working in harmony to each other and have the greatest potential for further work. After choosing the right concept of suspension conforming to the demands and wishes that we have received until, we have further evaluated the mechanism for transition between driving and transport position. We believe that we have fulfilled our task to build something simple but usable which was the goal of the project.

Balancing the body and the transition between the driving and transport mode are two concepts that have a simple design solution with a few components and moving parts, and is completely free from electrical interference. To reduce the risk of any failure that may occur, it feels good to have simple concept selection.

6.1 Final solution

The final solution is the two concepts from evaluation 1 and 2 combined. See figure 6.1-1.

Figure 6.1-1
The solar panels needed to be placed a little bit higher over the chassis to make room for the balancing mechanism, which is shown in figure 6.1-2.

Figure 6.1-2

The red/pink rods are turnbuckles which provide fine tuning of the attitude of the whole chassis. The leaf spring holds the chassis up and is connected to both the front and middle suspension arms (blue and bright green). It is also connected to the so called balance link (orange) which allows the whole suspension to rotate around its axle. The front and middle suspension arms (blue and bright green) are mounted on the same axle (inside each other) (see figure 6.1-3) and are moving freely and independently of each other. It is only the leaf spring that holds them in position.
For better reliability, the ends of the leaf spring could be secured sliding in a slot in each of the suspension arms.

The leaf spring allows the rover to be folded completely during the journey in the space capsule (see figure 6.1-4), regardless if it is caused by just the G-forces or if it is in some way strapped or fastened to the floor by something, to make it take up less space and so that the suspension arms not must be able to hold up the load of the whole rover during the 20-G forces period.
The distance between all the wheels are the same and the joints of the suspension arms are also centered. This results in that all the wheels get evenly distributed force/pressure from the ground (given that the mobility system is placed against the center of gravity of the chassis, making no or very small moment to the mobility system).

This is good because then all the wheels have the same qualification to clear obstacles.

6.2 Future work

Things that are needed to be done to the rover are:

Embodiment design of the steering, motor mounts and “gearbox” if that is needed. It is possible that the motors are operating better if they are allowed to turn faster than one turn in a couple of seconds. The speed of the rover is low and high torque is just good for the reliability and the ability to climb over obstacles. Those who will work with this can investigate if there are motors with high torque enough that operates well on that low rotational speed, or if a gearbox is needed, and in that case, make an embodiment design of it.

After that a detail design can be done on the whole mobility system. This can reasonably be divided to two different groups.

An embodiment design was done on the deployment arms 2013. A detail design needs to be done at that part too.

After that a detail design can be done on the exterior of the chassis. The interior of the chassis can first be done when it is known everything what shall fit inside the chassis.
7 Critical Review

In the beginning of this project we were a bit mislead or confused. Partly because we thought we should begin with the detail design and partly because the process on the moon (how base station works, and how the rover gets the rolls, etc.) was not clear or fully certain. After a while when we had gone through the background and the last years work and some internal discussions we realized that the last year work was not a foundation enough to start a detail design from. Instead we did a more detailed embodiment design. Therefore some time were spilled due to that.

Except that, the work has gone very smoothly and we are very satisfied with our result.

Unfortunately, because the rover is a very big thing to develop, we only had the time to do embodiment design. It is first in the detail design one get in touch with solid mechanics, machine elements, optimization, calculations and things like that. Thus we unfortunately have not got the chance to practice these things in this project.

We wanted to build a prototype of our final solution, but unfortunately we ran out of time at the end. Therefore no prototype is built yet.

We were also focusing at the wrong things like the weight of the antenna rolls. According to the last year work the antenna rolls could weigh up to 75 kg, which would most likely affect the balance of the rover very much if it was so. Therefore we put a lot of energy into it at the beginning. In the end of the project we found out that the rolls would weigh much less which would not affect the construction of the rover as showed in Appendix 3.

There have not been many people who have been involved in this project. The work has been done quite independently with some help of our instructor. Due to time boundary we was limited to do much of the work behind computer screen and very little in workshop which would allowed us to clearly see concepts function in praxis too, and our work would not have to rely just on calculations. How something is made in praxis allows us to conform that every detail is functioning as expected and even match its calculations.

However, in the end we are very satisfied with this project. It has been a good practice in the process of constructing. And many ideas for concepts have been worked through. Which we find has been very good for our personal development.
Community, environment and economy

This project does not affect community or environment directly, because it is just about the development of a mobility system. The manufacturing can anyway affect the environment a little, but that will be very little because it will just be produced once in one specimen. The materials are not decided yet either so the environmental effects are unknown yet. If there would be any, it would just be the ones caused by the manufacturing of the materials and components because the rover is supposed to be sent to the moon. What happens with the rover on the moon after it is ready with its task doesn’t affect us in any way. Any recycling must not be considered.

The technology we use does already exist and doesn’t need any research about how it affects community and environment. The scientists will most likely have a great profit from the radio telescope (DALI) that is going to be built on the moon. And that may not give the community any benefit directly, but hopefully and most likely indirectly. Research about one thing often leads to good discoveries that can be applied in other areas. In other words, many people maybe don’t care about if we get better understanding of for example dark matter, but that research might lead us to things that can in a direct way be helpful for community in the shape of for example new materials or new discoveries in physics that might improve electronics or other things that we can have use of, things that will be directly helpful for community.

Research is most often good for community in some way even if it is research that is not about anything that helps community directly. An example can be given: Formula 1 does not give community more than entertainment, so why put so much research and resources into it? If it would not be for formula 1 we would most likely not have ABS braking systems in our cars today.

This project (development of mobility system) may not lead technology further, but it is anyway a part of the DALI project, which will be a good thing for research.
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Appendix 1 - Concepts of Suspension
Appendix 2-Concepts of transition mechanism
Appendix

T6

T7 a

T7 b
Appendix 3 – Technical data of rover

<table>
<thead>
<tr>
<th>Rover Components</th>
<th>Qty</th>
<th>Unit Mass (kg)</th>
<th>Total Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm Electronics Box</td>
<td>1</td>
<td>107</td>
<td>107</td>
</tr>
<tr>
<td>Camera Mast</td>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Antenna Roll</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Robotic Arm</td>
<td>1</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Fixed Body Stereo Camera Pair</td>
<td>2</td>
<td>0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>Cartidge for 4 Antenna Rolls</td>
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<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Rover Suspension</td>
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<td>35</td>
<td>35</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>9</td>
<td><strong>170.25</strong></td>
<td><strong>170.5</strong></td>
</tr>
</tbody>
</table>

System Specifications

- Rover mass: 64.8 kg (desired, with projected technology advances)
- Rover base dimensions: 2 m long x 1.6 m wide x 1.75 m high
- Payload capacity: 6 x 6 kg spools, 2 kg hub
- Deployable 5 m relay antenna
- Sensing/Navigation
  - Panorama and navigational stereo camera pairs on mast for navigation and station keeping
  - Forward and aft hazard avoidance stereo camera pairs for driving
- Robotic arm
  - End effecter designed to grab and unroll spool and hub
- 25 km traverse capability for lifetime
- Rover speed: 5 cm/s
- Rover power: Desired to run on continuous solar power
- Deployment time: 12 days
  - 1 day for unstow and system checkout
  - 3 day to reach station location
Appendix

- 1 day for hub deployment
- 6 days for array setup (1 day per array leg)
- 1 day for final positioning of rover, connection to hub, and antenna deployment
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