Design of a torque measurement device for the ExoMars rover

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Chapter 1

Introduction

As a part of the Aurora Exploration Programma, ESA will launch the ExoMars mission in 2013 to Mars. This mission consists of three modules. The orbiter, which functions as a data relay satellite. The ground station which measures various environmental variables and the rover which travels over the Martian surface. This rover is equipped with a lightweight drilling system, a sampling and handling device, and a set of scientific instruments to search for signs of past or present life.

In order to test and verify the locomotion performance of the ExoMars rover, a torque measurement on all six wheels is desired. Furthermore, with these measurements it is possible to implement advanced control algorithms for the autonomous operating rover. In addition it might provide an insight in the properties and conditions of the Martian surface.

In developing the torque measurement device, the specifications supplied by the ESA are kept in mind. Important factors to reckon with are maximum velocity, wheel diameter and width and mass reduction. Of course one should also take into account the fact that these measurements will take place on the Red Planet and the device should survive the launch from Earth and the descent to Mars.
Chapter 2

Design criteria

2.1 General requirements

For the design of a torque measurement, the entire inwheel drive system is considered, resulting in a complete internal wheel design, ready to use.

There are a number of criteria to the design of the wheel unit. First of all, of course all the 'normal' problems of a launch into space must be dealt with. The G-forces and vibrations that occur during the launch and the transition from Earth atmosphere to the vacuum of space. The radiation in space can also be very destructive for the device. When the module arrives on Mars, it will operate in very different circumstances in comparison to from Earth. In table 2.1 some main differences between Earth and Mars are presented.

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravity</td>
<td>9.80</td>
<td>3.71</td>
</tr>
<tr>
<td>pressure</td>
<td>101.3</td>
<td>0.6</td>
</tr>
<tr>
<td>average temperature</td>
<td>287</td>
<td>210</td>
</tr>
<tr>
<td>minimum temperature</td>
<td>200</td>
<td>140</td>
</tr>
<tr>
<td>maximum temperature</td>
<td>330</td>
<td>300</td>
</tr>
<tr>
<td>wind speeds</td>
<td>5-8</td>
<td>2-10</td>
</tr>
<tr>
<td>density atmosphere</td>
<td>1.2</td>
<td>0.0155</td>
</tr>
</tbody>
</table>

Table 2.1: Comparison of conditions on Earth and the Red Planet

The temperature, gravity and in addition radiation are the environmental variables of most concern in developing the torque measurement device. To prevent damage to the device due to differences in thermal expansion most components are manufactured from the same material. To further minimize thermal and internal tension problems it is critical to design 'statically determined' -i.e.- fixing every degree of freedom only once [1]. By applying this design principle wear, hysteresis and fatigue due to undefined tensions in the device are brought to a minimum.

Gravity is much smaller on Mars compared to Earth, important for the magnitude of the interaction forces with the ground surface.

Radiation is very intense on Mars. Magnetic radiation, solar winds etc could lead to disturbance in the measurement or even failure of the device, depending on which measurement principle is used.
As mentioned, the global specifications of the ExoMars rover are provided by ESA and are listed in table 2.2. These specifications are guidelines and can be stretched to a reasonable extent. The maximum velocity of the rover of 200 meter per hour should be maintained for a short period to be able to get the rover out of trouble. Furthermore a self-braking reduction of is desired, avoiding the use of brakes. These will only add weight and complexity to the design. Finally, the total weight of the design must be kept as low as possible.

### Table 2.2: Several ExoMars rover specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>200 [kg]</td>
</tr>
<tr>
<td>Wheel diameter</td>
<td>350 [mm]</td>
</tr>
<tr>
<td>Wheel width</td>
<td>100 [mm]</td>
</tr>
<tr>
<td>Maximum velocity</td>
<td>200 [m/h]</td>
</tr>
<tr>
<td>Reduction</td>
<td>self-braking [-]</td>
</tr>
</tbody>
</table>

2.2 General design concept

Measuring the torque that acts on each of the wheels of the ExoMars rover can be done in several ways. The easiest way is to measure the ingoing current of the motor, since these are controlling signals and thus known, and calculate the torque. However there is a reduction of approximately 1:1000 between the motor and the wheel. Considering the unknown losses in the reduction it is vary hard to say anything about the forces acting on the wheel by only measuring the current. Thus a measuring device must be placed as close to the load as possible.

Another way of measuring the torque is to measure a deformation, either by measuring the strain or the displacement of an elastic element. To do this, an element with a certain stiffness is implemented in the system, for instance a leaf spring.

In the first designs elastic elements are added between the driving motor and the wheel tread (see Figure 2.1). However, by inserting a low stiffness element in your drive line, the overall performance of the system decreases, the possibility arises that roll-up occurs. This results in unpredictable and therefore dangerous performance of the drive line, thus prohibiting simultaneous drive of the six wheels and the aim of intelligent torque feedback.

![Figure 2.1: Several design sketches](image-url)
The second design does have an elastic element, however it is not placed directly in
the drive line. In this way it's possible to measure the strain or displacement without
losing performance of the system. To do this a planetary gear set is implemented. The
motor drives the sun gear of the planetary set. The sun gear drives the planet gears
wheels, which drive the annulus gear, which in this case is the inner side of the wheel
tread. The planet carrier is suspended in three leaf springs on a fixed world. This fixed
world is rigidly mounted on the wheel axle, which is rigidly mounted to the fork that
supports the wheel. The situation is sketched in Figure 2.2. Now if the wheel is driven,
the transmitted torque causes the leaf springs to bend slightly, which can be measured
as a strain or a displacement.

Since the axle is fixed, the wheel must be supported in bearings on the axle. This
gives an extra advantage since all forces acting on the wheel are directly passed on to
the axle meaning that the inwheel drive has only the drive torque to transmit. This
results in a good separation between the torque and the other forces, important for ac-
curate measurement. Also it means that the measuring system can be lighter and less
complex.

Figure 2.2: Sketch of one of the measuring points in the final design
2.3 General measuring concept

To measure the deformation of one of the leaf springs it is possible to use a strain
gauge. However, there is little to no experience in using strain gauges on leaf springs
that can cope with the extreme conditions of a launch, the vacuum of space and the
Red Planet. Therefore this measuring method was rejected.

An other way to measure the leaf spring deformations is to measure the displacement
between the carrier and the fixed world. The displacement perpendicular to the leaf
spring is of a much higher order than the strain, approximately 1 mm versus 200 \( \mu \). So
it should be much easier to make a good measurement of the displacement. See also
figure 2.3. The measurement of this displacement can be executed in several ways,
discussed in more detail in chapter 5.

![Figure 2.3: Sketch of a deformed leaf spring](image-url)
Chapter 3

Analysis

3.1 Forces

Motion of the rover is possible because the driving force of the drive train is higher than the magnitude of the resistance forces between the wheel tread and the Martian surface. In general these resistance forces are the following:

1. Rolling resistance
2. Grade resistance
3. Air resistance

To make an analysis of the ground surface, the parameters of soil can be determined from the value of the rolling resistance.

3.1.1 Rolling resistance

Motion of a wheel consists of two forms, rolling and sliding. Rolling exists as long as the contact area of the wheel and the surface on which it moves, have no relative motion to each other. Otherwise the wheel starts to slide. This can occur during fast acceleration of when traction is very low in lose soil or on steep slopes. Sliding is to be prevented in any situation due waste of power and the lack of contribution to the movement of the rover.

The forces acting on a wheel are depicted in figure 3.1.

The kinetic friction between the wheel and the ground is given by

\[ F = W \mu \]  

With coefficient of kinetic friction \( \mu \). \( W \) is the weight in Newton. The condition for a rolling motion is

\[ P_{max} \leq W \mu \]  

The driving force P can assume two forms:

1. External force, e.g. pushing or pulling. See figure 3.1(a).
2. Internal force, originating in the vehicle and translated as torque to the wheel axis. The frictional reaction of the ground is then the actual driving force. See figure 3.1(b).

Equation 3.2 can now be rewritten to give the maximum torque transferred to the ground by the wheel.

\[ M_{max} = r W \mu \]  

Opposed to the rolling progression of a wheel is the rolling resistance. When a (rigid) wheel moves over the ground, the ground will be deformed and at the pressure center
a normal force \( N \) will act. This force consists of a vertical component opposing the weight of the wheel and a horizontal component, representing the rolling resistance, see figure 3.2. The equilibrium of these forces can be stated as follows:

\[
P = Rr = W f_0 / r = W \mu
\]  

(3.4)

With \( f_0 \) the coefficient of rolling resistance. The force required is thus only dependent of \( f_0 \), since vehicle weight and tyre radius are already specified. In general, it’s quite difficult to accurately determine this coefficient. It is dependent of the tire diameter, wheel pressure, velocity and of course the soil on which the wheel rolls. Since wheel pressure or stiffness is unknown and the tire diameter is already specified by ESA, and the velocity is very low, only the soil is of importance. In figure 3.3 it is shown that \( f_0 \) lies, for a wheel with a diameter of 350 mm, somewhere between 0.1 (medium hard soil) and 0.4 (heavy sand).

The rolling resistance \( F_R \) is proportional to the tire normal force.

\[
F_R = f_0 F_N
\]  

(3.5)
Assuming that the rover always drives on six wheels, and only walks on less than six, the normal force of one wheel is calculated. The normal force of one wheel is equal to

\[ F_N = \frac{1}{6} \cdot m g = \frac{1}{6} \cdot 200 \cdot 3.71 = 123.7 \text{ N} . \]

This gives a rolling resistance that varies between \( F_R = 12.4 \text{ N} \) and \( 49.5 \text{ N} \).

### 3.1.2 Grade resistance

Grade resistance \( R_g \) is the component of the vehicle weight acting downhill. It is given by

\[ R_g = W \sin \theta \quad (3.6) \]

As ESA specified the maximum slope the rover should be capable to climb 25 degrees (in soft soil). This gives a maximum grade resistance for one wheel of 52.3 N. Compared to the rolling resistance this is quite big, however the rover will only climb steep slopes when in easy terrain.
3.1.3 Air resistance

The air resistance on Mars can be neglected because the density of the atmosphere is very low. The drag force \( F_D \) can be calculated as follows:

\[
F_D = C_D A_{ref} \left( 0.5 \rho U_\infty^2 \right)
\]

With

\[ A_{ref} \approx 2 \text{ m}^2 \]
\[ C_D \approx 0.5 \]
\[ \rho = 0.0155 \text{ kg/m}^3 \]
\[ U_\infty = 5 \text{ m/s} \]

This gives an air resistance of approximately 0.19 N. This is very low compared to the rolling resistance and grade resistance and can therefore be neglected.

3.1.4 Wheel torque

With a wheel diameter of 350 mm the torque on each wheel will be between 2.2 and 10.9 Nm. This is of course an approximation. The rolling resistance and grade resistance are the most important forces acting on the wheel. The rolling resistance lies between 12.5 and 50.0 N and the grade resistance between 0 and 50 N approximately. Considering that the rover will not climb a 25° slope in very heavy sand the total force acting on one wheel will vary between 12.5 and 62.5 N.

3.2 Leaf springs

The dimension the leaf spring must be such that it is possible that the leaf spring goes through the carrier, see section 4.2. This leaves the thickness and the height for adjustment. For a good measurement the stiffness of the leaf spring must be such that it will bend between 0.5 and 1 mm under maximum load. With the following equation the stiffness of the leaf spring is calculated.

\[
C_b = \frac{F_b}{f} = \frac{Eht^3}{l^3}
\]

With

\[ F_b = 50 \text{ N} \]
\[ E = 1.21 \cdot 10^{11} \text{ N/m}^2 \]
\[ l = 20 \text{ mm} \]
\[ f = 0.5 \cdot 1 \text{ mm (target)} \]
\[ h, t: \text{ free material parameters} \]

With h=30 mm and t=0.5 mm this results in a deflection \( f \) of approximately 880 \( \mu \). To see if this approximation is reliable, several FEM analysis are done. The results are shown in table 3.1.

<table>
<thead>
<tr>
<th>spring thickness [mm]</th>
<th>stress [MPa]</th>
<th>strain [( \mu )]</th>
<th>displacement [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>590</td>
<td>4800</td>
<td>1.40</td>
</tr>
<tr>
<td>0.60</td>
<td>400</td>
<td>2800</td>
<td>0.82</td>
</tr>
<tr>
<td>0.75</td>
<td>290</td>
<td>2100</td>
<td>0.44</td>
</tr>
<tr>
<td>1.00</td>
<td>200</td>
<td>1200</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 3.1: Maximum values for different leaf springs
The yield strength for Ti-Al-V is 805 MPa. From these simulations a thickness of 0.6 mm seems a better choice because a thickness of 0.5 mm gives a too high value for the stress and strain. With 0.6 mm thickness only half of the elastic region is used and there is still 0.8 mm displacement. In addition to make the system more statically determined incisions can be made in the leaf springs, however this is of large influence to the stiffness of the leaf springs.

3.3 Fixed world

Also for the fixed world several designs were considered. For a good measurement it’s very important that the fixed world is very stiff and has practically no deformation. But to create a very stiff element there’s always a lot of material needed. After considering several alternatives (appendix A) the design ‘concept E’ shown in figure 3.7 was chosen. From FEM analyses it appears that all the designs have a non negligible deformation. This deformation is the bending of the three arms coming from the centre to the outer ring as depicted in figure 3.5. To see how sound the different designs are, the analysis are done under a larger load than estimated. This is done to see if the designs are able to withstand higher (disturbance) forces.

![Deformation of fixed world under load](image)

The deformation from figure 3.5 is a linear deformation for which can easily be compensated with calibration of the torque calculating algorithm on Earth. Also the outer ring forms a S-shape, see figure 3.6. Due to the symmetry and the axial stiffness of the leaf springs the measurement points will have no axial deflection as is seen in the figure.

To increase the stiffness of the fixed world element more material is needed which will result in a higher weight. Making the element stiffer would never result in zero deformation. So a compromise was made between element stiffness and weight.

To make the stiffest beams possible with low weight a honeycomb structure was chosen. This will give the highest stiffness/weight ratio as possible. Making a honeycomb structure of Ti-Al-V is not easy but very well possible [8]. In table 3.2 the difference
in weight of each of the alternatives is shown, together with the maximum deformation obtained from FEM analysis. A compromise between weight and deformation was made and concept E is chosen as the final design.

<table>
<thead>
<tr>
<th>concept</th>
<th>weight [kg]</th>
<th>deformation [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$228.9 \times 10^{-3}$</td>
<td>$6.40 \times 10^{-2}$</td>
</tr>
<tr>
<td>B</td>
<td>$349.3 \times 10^{-3}$</td>
<td>$3.57 \times 10^{-2}$</td>
</tr>
<tr>
<td>C</td>
<td>$362.7 \times 10^{-3}$</td>
<td>$3.90 \times 10^{-2}$</td>
</tr>
<tr>
<td>D</td>
<td>$924.2 \times 10^{-3}$</td>
<td>$5.00 \times 10^{-2}$</td>
</tr>
<tr>
<td>E</td>
<td>$140.2 \times 10^{-3}$</td>
<td>$4.35 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Table 3.2: comparison of different concepts
Chapter 4

Design and manufacturing

Based on the executed analyses several design choices are presented here. The individual parts are discussed from the main part towards the whole design. Starting point in this approach is the actual measuring device, the planetary set attached to a fixed world with leaf springs. For each part the design is discussed and in addition the manufacturability. In general the parts are manufactured from a Titanium-Aluminum-Vanadium (Ti-Al-V) alloy, considering its high tensile strength (even at high temperatures), light weight, extraordinary corrosion resistance, and ability to withstand extreme temperatures. Also for all the gears the shown outside radius is the pitch radius. The total design results in a torque measuring device included in the driving line, weighing only 2.017 kg (including gear and motor, excluding wheel enclosure and the measuring device).

4.1 The planetary set

The planetary gear set must be able to transmit torques of about 10 Nm without any deflection in axial, radial and tangential direction. Tangential deflection influences the measurement accuracy and axial or radial deflection results in excessive wear of the gears and unwanted shear loads on the leaf springs.

![Figure 4.1: Drawing of the four identical carrier plates](image-url)
The most stiff construction of the carrier is two solids bolted together with the planet gears in between. In addition the solids are carried out as two sandwich structures, consisting of two plates each, providing the same stiffness while decreasing the weight. The four identical plates are simply manufactured by cutting slices of rod material and then drilling the holes simultaneously in all the plates. Mounting and spacing the plates occurs through spacers between the plates and bolting them together. This is discussed below and in section 4.2. The planet gears are press-fitted on normalized bearings (INA) which are supported by two-pieced bushings in the carrier. Through the unthreaded piece a bolt is screwed into the threaded piece, clamping the planet bearing by pulling the carrier sandwich panels together. Spacers between the sandwich plates and bearings provide the correct axial position information. The planets are manufactured by slicing rod material, milling the sides of the slices to reduce weight, drilling a hole in the middle and cutting the teeth.

The sun gear is simply mounted on a sliding or a normalized needle bearing (INA) on the axle. However it is slightly more complex since it consists of two ‘separate’ gears (see Figure 4.2(b)). These gears are manufactured separately and the smaller gear can be bolted to the larger gear. The radii of the gears are discussed in section 4.5. Combining the parts leads to Figure 4.3 where the complete carrier with and sun gear are shown.
4.2 Leaf springs

The dimensions of the elastic part of the leaf spring result form simple stiffness calculations combined with extensive finite element calculations. In addition the leaf springs form the equivalent of a guiding system and from literature [1] is obtained that the load must be applied in the middle of the elastic part of the leaf spring to minimize the bending moment on the leaf spring. Thus the leaf spring is mounted through the carrier. Furthermore the mounting face between the leaf spring and the fixed world is notched to make sure that the leaf spring remains perpendicular to the fixed world. The leaf spring can be manufactured by wire spark eroding the vertical contours, and drilling and milling the required holes and curves in horizontal direction. After that the bushings can be slotted in the drilled holes.
At the same time the mounting of the leaf springs is used to bolt the carrier plates together with the required spacers in between. The same principle of two-pieced bushings, through which the carrier plates are bolted together, is used, however one half of the bushings is directly attached to the leaf spring.

### 4.3 Fixed world

The design of the fixed world disc follows directly from section 3.3. As mentioned the disc consists of a honeycomb sandwich panel. In the areas where the leaf springs and thus the carrier is bolted to the disc, solid blocks are manufactured between the sandwich panel. This also accounts for the flange that provides stiffness around the axle. Note that this is a process that has to occur during the manufacturing of the honeycomb itself. Normalized splines are milled in the flange to make sure that the fixed world doesn't rotate with respect to the axle.

### 4.4 Axle

The axle is mounted with normalized splines in the fork (discussed in section 4.7). For convenience the splines are simply drawn on the axle. Furthermore the axle is hollow so wiring can be lead through it. For the width of the sun gear a groove is milled for a sliding or needle bearing. The thicker part gives the fixed world its axial position information whilst the splines provide tangential fixation. In Figure 4.6 can be seen how the mechanism is mounted on the fixed world which in it's turn is mounted on the axle.

![Fixed world and Axle](image)

(a) Fixed world  
(b) Axle

**Figure 4.5: Drawings of the fixed world disc and the axle**

### 4.5 In-wheel motor and reduction

For driving the wheel a standard solution is chosen, namely an 8 Watt brushless DC motor. More details are provided in appendix B. The motor has a build-in pre-reduction of 1:250. The sun gear has a transmission ratio of 1:2.33 towards the wheel inner gear (see the next section). The overall reduction can be tuned by choosing the radius of the smaller 'separate' sun gear and the output gear on the motor. In this case a total ratio of 1:1500 is achieved. The motor is mounted on a simply manufactured support, which is bolted or welded to the axle. In Figure 4.7 the transmission from the motor gear via the sun gear to the planet gear can be seen clearly.
In this report only the inner part of the wheel is considered. As mentioned the wheel is supported directly on the axle with bearings. Note that these bearings must also form a seal so the inner mechanism remains free of dust and sand. The wheel has a separate lid which is bolted on after the inner mechanism is completed. Furthermore the wheel is driven by the planet wheels on a gear manufactured on the inner radius of the wheel. In Figure 4.7 one can see the wheel mounted through bearings on the axle.

### 4.6 Wheel with inner gear

In this report only the inner part of the wheel is considered. As mentioned the wheel is supported directly on the axle with bearings. Note that these bearings must also form a seal so the inner mechanism remains free of dust and sand. The wheel has a separate lid which is bolted on after the inner mechanism is completed. Furthermore the wheel is driven by the planet wheels on a gear manufactured on the inner radius of the wheel. In Figure 4.7 one can see the wheel mounted through bearings on the axle.

### 4.7 Fork

The fork is actually a part not considered in this report since it doesn’t belong to the inwheel drive. However it is important to give an idea of the way the axle should be mounted. A space is left open between the wheel and the fork for some sort of tire providing the necessary spring-damping characteristics. The fork has normalized splines to fit on the axle and clamps both the wheel bearings. Also through a spacer the fixed world is clamped to the thicker part of the axle. Adding the fork completes the design which is shown in Figure 4.7
Figure 4.7: Cross section of the complete design
Chapter 5

Measurement devices

To measure the displacement of the leaf springs different types of sensors can be used. Three different types of measuring principles are discussed here with their advantages and disadvantages. The measuring device can be positioned on either the carrier enclosure or the fixed world plane. To make sure the rover remains mobile when one or more leaf springs break down a security mechanism must be added between the carrier and the fixed world. In this mechanism, sketched in figure 5.1, the measurement device can be integrated.

![Figure 5.1: Sketch of fail-safe mechanism](image)

5.1 Fotonic measurement

The fotonic sensor is a displacement sensor containing two groups of fiber optics.[6] One set, the transmitting fibers, is connected to a light source. The other set, the receiving fibers, is connected to a photo detector. These two groups of fibers are bundled into a probe. The light generated from the source is channeled through the transmitting fibers to the probe tip. The light then travels to the target surface and part of it is reflected back to the probe. A portion of the reflected light is caught by the receiving fibers and transmitted to the photo detector where its intensity is measured. The intensity of the reflected light is a function of distance between the probe tip and the target surface, see figure 5.2.

The advantage of this type of measurement is that it has no moving parts and does not come into contact with the measured object. There will be no disturbance in the measurement due to the measuring device. The typical specifications of a fotonic sensor are listed in table 5.1.
Another optic measure principle is to use a light source and a photo diode. However, now not connected to optic fibers, but fixed directly onto the fail safe mechanism. From the light source the light goes through a hole and then falls onto the diode. This can be implemented in the fail safe mechanism for example. See figure 5.3. When the carrier moves with respect to the fixed world, the photo diode will receive less light from the light source because the hole is not exactly between the light source and the diode anymore. For different displacements the diode receives different illumination and thus a difference in output voltage. When calibrated this results in a value for the displacement of the leaf spring.

### Table 5.1: Fotonic sensor specifications

<table>
<thead>
<tr>
<th>Diameter</th>
<th>2.75 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>70 [mm]</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>63 [mV/µm]</td>
</tr>
<tr>
<td>Linearity</td>
<td>± 1 %</td>
</tr>
</tbody>
</table>

### 5.2 Through hole measurement

Figure 5.2: General fotonic sensor

Figure 5.3: Through hole measurement
The advantage of this measurement is that all the devices are in the wheel and only data cables lead back to the rover. This optic measurement also doesn’t touch the moving leaf spring and causes no disturbance. Furthermore it’s very compact and light. However the resolution of this type is not very high. Further specifications are listed in table 5.2.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>9 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>5 [mm]</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>? [mV/µm]</td>
</tr>
<tr>
<td>Linearity</td>
<td>? %</td>
</tr>
</tbody>
</table>

Table 5.2: Through hole sensor specifications

### 5.3 Differential Transformer

The Linear Variable Differential Transformer (LVDT) is a broadly used variable-inductance transducer. It is an electro-mechanical device designed to produce an AC voltage output proportional to the relative displacement of the core and the coil assembly, as illustrated in figure 5.4. The core must be connected to the leaf spring. When the leaf spring moves, the movement of the core will induce an output voltage. For higher frequencies of the voltage a higher resolution is obtained.

![LVDT Diagram](image)

Figure 5.4: Typical LVDT

The advantage of this measurement is that it has low cost and is robust. In theory it has an infinitesimal resolution and a good signal to noise ratio. The problem with this device is that it has to make contact with the leaf spring and it is sensitive to disturbance from other magnetic fields.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>10 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>100 [mm]</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1 [mV/µm]</td>
</tr>
<tr>
<td>Linearity</td>
<td>± 0.5 %</td>
</tr>
</tbody>
</table>

Table 5.3: LVDT sensor specifications
5.4 Comparison

The different types of measuring devices all have their advantages and disadvantages. For a measurement on Mars, a comparison between the three methods is made in table 5.4. For building a prototype and testing it on Earth, the measurement device probably has different requirements than the measuring device for Mars. Resistance against temperature change and (launch) vibrations was not studied, and is therefore not accounted for. A choice should be made considering the pro’s and cons of the different types of measurement systems. For a sound measuring device for Mars, more profound studies are necessary.

<table>
<thead>
<tr>
<th></th>
<th>Fotonic</th>
<th>Through hole</th>
<th>LVDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>– –</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Mass</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Peripheral equipment</td>
<td>– –</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Robustness for Martian conditions</td>
<td>+</td>
<td>+</td>
<td>– –</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+</td>
<td>– –</td>
<td>++</td>
</tr>
</tbody>
</table>

Table 5.4: Comparison between measuring devices (– –,0,+,++)
Chapter 6

Conclusions and recommendations

A planetary set suspended in leaf springs can be used to measure the torque that is exerted at each wheel of the ExoMars rover. The concept relies on a combination of proven constructive and measuring solutions. The constructive part of the measuring device consists of an elastic element which doesn’t compromise the performance of the inwheel drive. Using this device gives the ground crew access to accurate data concerning the driving forces on and reaction forces to the wheel.

The collected data provides not only an insight in the situation of the vehicle. The control of the rover can be upgraded from simple feedforward control to advanced feedback control. For instance only the wheels that have traction can be used to drive the vehicle in order to save power.

Using terra-dynamics the measurements can also be used to gain knowledge on the conditions of the Martian surface. By evaluating the reaction force on the wheel, and thus the amount of torque needed to drive the wheel, one can determine the properties of the surface.

To collect data in the hostile environments of space, given the additional fact that the equipment must first of all survive the launch, several measuring methods are evaluated. It remains difficult to predict which method will hold best. More extensive knowledge concerning the working conditions is required. However a conclusion can be drawn with regards to several technologies and simple seems best. A through hole measurement is not only simple, it is also small and light and no complex peripheral equipment is required. To determine whether or not the resolution of this measurement is sufficient more research is required.

Currently the required power is provided by an off-the-shelf electric motor with a build-in prereduction. The inwheel drive can be more efficient in terms of space and power requirements and also the applicability for outer space purposes. More knowledge is required with respect to the current actuators used on the Red Planet. Possibly specific drives should be designed.

Also the attachment of the wheel to the legs and the wiring through these legs requires more analysis. In the design however, by implementing an axle, these matters are made less complex.

The mass of the drive line including the torque measurement comes down to 2.0 kg per wheel.
Appendix A

Fixed World alternatives

Figure A.1: Alternate fixed world designs
Appendix B

The inwheel drive
Figure B.1: Electric engine specifications
Figure B.2: Gearbox
Bibliography


