Magnetic compliant suspension concept for space robotics

MAGNETIC COMPLIANT SUSPENSION CONCEPT FOR SPACE ROBOTICS

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Abstract – This paper proposes a Dual-Magnet Magnetic Compliance Unit (DMCU) for use in medium sized space rover platforms to enhance terrain handling capabilities and speed of traversal. An explanation of magnetic compliance and how it can be applied to space robotics is shown, along with an initial mathematical model for this system. A design for the DMCU is proposed along with a 4-wheeled DMCU Testing Rig.

Index Terms – Magnetostatics, Robot Motion, Space exploration, Space vehicles

1. INTRODUCTION

Robotics systems are a very important part of space exploration. There is currently much interest in enhancing the versatility of space robotic rovers. Current rover configurations have limitations due to the forces generated when impacting objects whilst traversing unstructured terrain. These limitations are necessary to maintain system stability and increase the chassis/rovers life-span by reducing mechanical vibrations which transfer to the equipment contained within the rover. Therefore the rovers speed is limited to reduce the magnitude of forces that occur during these impacts. Unstructured terrain also limits the maximum distance a robot can travel autonomously as the chassis design and capabilities restrict the path that the rover can navigate. If the rover could increase speed whilst maintaining stability over more complex terrain then the maximum distance that the rover could traverse could be greatly increased

Current robotics systems have used a number of approaches to incorporate compliance, such as material choices, traditional spring based suspension and active suspension. The Mars Exploration Rover (MER) [1], for example used mainly Titanium due to its strength to weight ratio, but also its ability to flex thus reducing some of the impact stresses generated during the rovers operation. The NASA Athlete [2], on the other hand, is able to actuate all of its legs so terrains that would normally be impassable to wheeled robots can be walked over by reconfiguring the robots chassis.

This paper proposes that certain limitations can be improved with the application of magnetic compliance to the chassis design. Magnetic compliance exploits the non-linear repulsive forces between opposing magnetic poles to create a compliant suspension system. The design, development and initial evaluation of a prototype dual-magnet magnetic compliance unit is presented and this paper describes a mathematical model for the compliance unit and compares the model with practical experimental data. The paper also discusses the development of the compliance unit, which required careful consideration of material properties with respects to magnetic fields and parasitic losses. For example if the chassis was made of Aluminium then the proximity of the magnetic compliance unit would generate Eddy (Foucault) Currents, thus introducing a damping effect within the compliance.

Paper Outline: Section 2 reviews a range of current rover systems and some of the limitations that they are subject to. Section 3 discusses the terrain handling requirements of space robotic rovers. Section 4 introduces magnetic compliance with initial mathematical models and testing. Section 5 describes the design of a prototype dual magnet compliance unit based on the results presented in Section 4 and a test rig that is currently under development to support further research.

2. SPACE EXPLORATION ROVERS

There have been many different rover systems used over the last 30 years for planetary surface exploration with the most successful to date being the MER platform [1]. The MER design was based on the Sojourner Rover [3] after very successful operation on the surface of Mars. The MER addressed some problems that were experienced with the Mars Pathfinder mission [4] which included the wheel design for soft surface traversal and lower nominal ground pressure, as well as the ability to communicate directly back to Earth rather than via a relay on the Descent Lander. The ExoMars Rover [5] currently being developed by the European Space Agency (ESA) will be fitted with more sophisticated object avoidance technology which should improve the robots surface traversal capabilities. A wide range of issues must be addressed, therefore, to enhance the capability of space robotic rovers. The following sub-sections consider rover limitations, environmental factors and communication constraints.

2.1. Rover Limitations

Rover systems on Mars all have to adapt to difficult terrain, which is why extensive testing is performed on

Earth [6] before a rover is put into service. The most successful chassis designs used in planetary exploration rovers are based on the rocker-bogie [7] design, as this keeps all wheels passively in contact with the surface whilst distributing load evenly. The rocker-bogie allows the rovers wheels to traverse objects larger than their diameter, so that normally impassable terrain to wheeled robots can be driven over without the need for constant course adjustments which consumes a lot of power.

The rocker-bogie system uses solid linkages, without compliance built into them, which means that the rovers speed needs to be limited to maintain stability over obstacles and not subject the rover to excessive forces or vibrations that occur when a wheel impacts an object. If these limitations were not in place the rover would suffer damage, such as torsional stress to the leg supports or excessive vibrations whist moving over larger rocks and uneven terrain.

When navigating autonomously a rover has to choose its path based on observations of the terrain as well as computation to confirm that it can safely traverse an obstacle. This takes time and often requires an operator on Earth to decide if the risk involved with the rovers current path is acceptable to the mission. If the rovers navigation system can see a clear and relatively smooth path ahead of the rover then it will travel as fast as it can to its next predefined coordinate, but with the limitations to the rovers speed to reduce vibrations this top speed is often not more than $10cm \cdot s^{-1}$ ($0.1m \cdot s^{-1}$) which greatly limits the distance that the rover can travel in a communications window with Earth. For example the MER is capable [8] under no load of a speed of $4.6cm \cdot s^{-1}$ ($0.046m \cdot s^{-1}$) and at full load a top speed of $2.6cm \cdot s^{-1}$ ($0.026m \cdot s^{-1}$).

2.2. Environment Factors

Surface composition can vary greatly depending on planet and even the location that a rover lands. Surfaces can range from deep drifts of loose dust [9] to huge boulder fields [10] which makes wheel design on the rover critical to mission success. The nominal ground pressure (NGP) is a calculation [11] that can help choose wheel parameters for a mission to limit wheel sinkage and resistance to motion. The calculation takes into account the number of wheels a robot has, the wheel width and radius as well as the robots weight. A low NGP will help the rover to traverse soft or loose surfaces, but the rover will also need to have enough traction whilst on the surface otherwise the robots motion will be very inefficient. The traction required to move the robot also affects the amount of torque that the drive train in the rover would need to generate, as the rover still has to be able to move in the event of drive failure in one or two of its wheels.

2.3. Communication Constraints

Communications lag is an important factor in how autonomous a rover has to be, as sending commands to Mars for example can take up to 20 minutes (depending on orbits around the sun), which would be 40 minutes round trip time for the operator on Earth to get updated position telemetry. This lag drastically reduces the amount of time for a decision to be made as to the rover's next move, because connections to Mars are made during a communications window which varies in length due to relative orbits. These windows can happen very far apart if Mars is orbiting the other side of the sun to Earth, as the sun blocks all communications with Mars.

3. TERRAIN HANDLING REQUIREMENTS

3.1. Drive Torques and Impact Forces

The drive train of space rovers needs to produce enough torque to not only move the rover but also lift it over obstacles and drive up slopes. If the rover is driving on a slope then it will be subject to the gravity of the planet that it is on which is rarely the same as the gravity on earth, for example the gravity on Mars [12] is roughly 38% of Earth's, meaning that 100kg on Earth would be roughly 38kg on Mars. This would make a rover tested on Earth much more capable on Mars as it would require less power to traverse objects and terrain. For example Eq. 1 shows the torque required (τ) for a 250mm diameter wheel (0.25m) to move a mass of 30kg up a 20° (θ) slope under normal Earth gravity ($9.81m \cdot s^{-2}$), with Eq. 2 showing the same situation but under Martian gravity ($3.72m \cdot s^{-2}$).

$$\tau = (0.25 \times 9.81 \times 30) \sin\theta = 25.1Nm \qquad (1)$$

$$\tau = (0.25 \times 3.72 \times 30) \sin\theta = 9.54Nm \qquad (2)$$

The above comparison shows that a motor in the drive train might be strained during testing on Earth but would be much more capable on the surface of Mars.

Even though these forces are reduced when operating on Mars the rover will still have to cope with impacts when its wheels climb over obstacles, which can create short, high magnitude vibrations that travel through the chassis and can damage the internal circuitry. Using the same values as before, the impulse force can be calculated Eq. 3 assuming that the wheel impacting a rock creates a step input and that the rover comes to a complete stop (v_1) in 0.5s (Δt), with an initial speed (v_0) of $0.046m \cdot s^{-1}$.

$$F = \frac{mv_1 - mv_0}{\Delta t} = \frac{30 \times (0 - 30) \times 0.046}{0.5} = -2.76kg \cdot ms^{-1} \qquad (3)$$

This force is negative because the impulse force is acting in opposition to the forward motion of the rover. The key to creating a durable chassis and reducing vibrations transferred to the rover is to reduce the magnitude of impulse forces that the rover is subject to.

3.2. Wheel Traction on Difficult Terrain

When driving over soft surfaces such as sand, not only does a rover require enough traction to move, but it needs a large enough surface area in contact with the ground to stop it from sinking into the surface and burying its wheels. To overcome this rovers need a low NGP with large diameter tyres to spread its weight. To help increase wheel traction on terrain such as soft sand or loose dust, rover designs have incorporated spikes into the surface of their wheels to allow them to claw their way over obstacles. For example, the MER rovers included paddles [13] around the wheels to help drag the rover over the soft sand. Wheels can incorporate compliance to aid traction; for example letting some air pressure out of a pneumatic tyre will increase the tyre's grip on a road car, but in space rovers pneumatic tyres are not practical. Instead the MER wheels were made from aluminium and had spiral shaped spokes linking the drive train on the wheels hub to the wheels rim. This spiral linkage could flex slightly allowing the rover to maintain pressure on the ground and deform slightly under impact conditions to reduce the impulse forces transferred to the rover's chassis if it was to drop off a rock (Fig. 1).

Figure 1. Spiral spokes that provide contact compliance in the MER Platform. (Courtesy NASA/JPL-Caltech)

3.3. Suspension in Current Rovers

Classical suspension systems which incorporate springs and dampers are widely used in road vehicles, but rarely in space robotics which normally favour solid linkage type suspensions such as the rocker-bogie which is use in the MER, Sojourner and ExoMars. Robots like the NASA Athlete and the MTR [14] use active suspension, where all the links in the chassis can be independently controlled and positioned. This gives the rover the ability to adapt its shape to the environment or obstacle that it is traversing. Active suspension requires more power compared to the rocker-bogie type, but it does allow the robot to traverse more challenging terrain. The NASA Athlete is able to lock its wheels and use them as feet that can be lifted individually allowing the robot to walk, which is very useful in boulder fields where wheels alone could get stuck. There has been some work done to incorporate magnetic compliance into legged robotics [15] which reduced the power required whilst the robot was moving, but this approach has yet to be applied to wheeled robots.

4. MAGNETIC COMPLIANCE

Magnetic compliance exploits the non-linear repulsive forces between two magnets which have been placed in opposition - opposing magnetic poles facing each other - to offer a novel suspension mechanism for robots [15]. We propose that this suspension mechanism can be applied to a space robotic rover to decouple it from the surface it is traversing, so that impacts do not damage the system.

This paper proposes using a number of magnetic compliance units on the wheel supports in a rover so that vibrations and displacements are handled as close to the ground as possible, although it would also be possible to mount a small compliance unit near the warm electronics box to add further isolation for the internal control circuitry.

4.1. Mathematical Model

Eq. 4 was used to simulate the initial magnet model (Fig. 2). This took into account variables including the magnets dimensions, field strengths and separation between magnet faces.

$$F = \frac{\pi \mu_0}{4} M^2 R^4 \left[\frac{1}{x^2} + \frac{1}{(x+2t)^2} - \frac{2}{(x+t)^2} \right] \quad (4)$$

μ_0 is the permeability of the intervening medium, in this case free space, R is the radius of the magnets in question. M is defined in Eq. 5 as the magnetic flux density B_0 divided by the permeability of the intervening medium μ_0 which is the same as before. The thickness of the magnets t is also required, as is the distance between their respective magnetic faces x. The resulting force F is measured in Newtons and is observed as the result of the variables and the interactions between them.

$$M = \frac{B_0}{\mu_0} \quad (5)$$

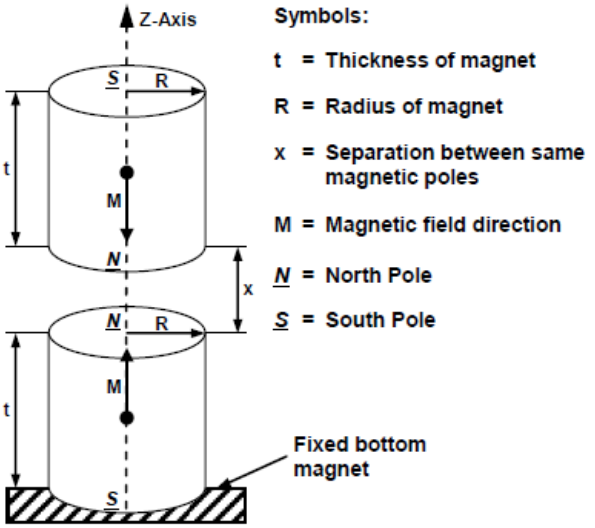

Figure 2. Two concentric cylindrical permanent magnets held so that the bottom magnet is fixed and the top magnet can only move in the z-axis.

4.2. Static Load Testing

Static load testing was carried out using a digital load cell (Fig. 3) made from steel. All ferrous metals will affect magnetic fields, but non-ferrous metals can also create disturbances to magnetic fields. This is due to an effect called Foucault Currents, which are present when passing a magnet past certain metals. For the static load testing a mixture of Delrin and mahogany was used to house the magnets, which de-coupled the magnets from the steel of the load cell.

To test the N42 Grade Neodymium Magnets a range of diameters, thicknesses and strengths were tested, with the final 10 magnets (Tab. 1) being mounted into the load cell for compression testing.

Figure 3. The testing rig, showing two magnets in the middle of a test sequence contained within the mahogany supports which de-couple the magnets from the steel frame of the load cell.

Table 1. Magnets tested in the load cell (Fig.3)

Magnet ID	17	19	20	21	23
Radius (mm)	2.5	2.5	2.5	2.5	3
Thickness (mm)	1	5	10	20	1
Magnitude (Tesla)	0.20	0.59	0.46	0.66	0.20
Magnet ID	33	34	43	44	54
Radius (mm)	4	4	5	5	10
Thickness (mm)	8	30	5	10	10
Magnitude (Tesla)	0.56	0.66	0.51	0.52	0.46

These magnets were compressed together giving a range of force measurements at varying distances between the magnets. These were then plotted against the theoretical data generated by Eq. 4. These plots are shown in Fig. 4 for one of the magnets, ID54.

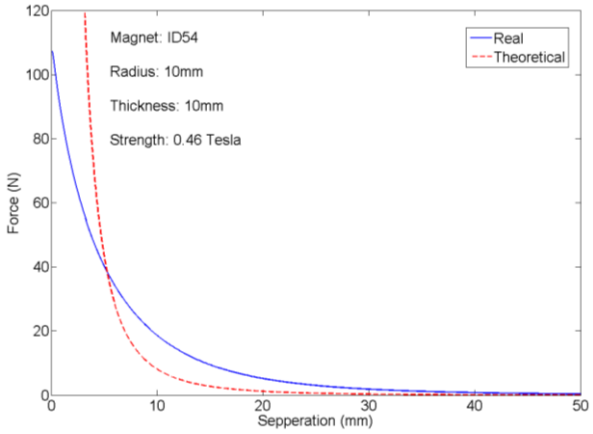

Figure 4. Graph showing the separation (mm) between the two ID54 magnets against the repulsive Force measured in Newtons (N).

The real world magnets whilst having a similar response to the theoretical did not achieve the same maximum force and deviated from the expected results. This is due to the N42 Grade Neodymium not being 'perfect'. In reality the magnetic material has imperfections and the opposing magnets will tend to de-magnetise each other.

The practical experiments show that the mathematical model requires further development, especially when the distance between the magnetic faces is less than the thickness of the magnets. This is being investigated as part of further research. Eq. 6 is a modification of Eq. 4 to express this observation.

$$F = \frac{\pi\mu_0}{4} M^2 R^4 \left[\frac{1}{x^2} + \frac{1}{(x+2t)^2} - \frac{2}{(x+t)^2}\right] \overset{aprox}{\Longrightarrow} when\ x > t \quad (6)$$

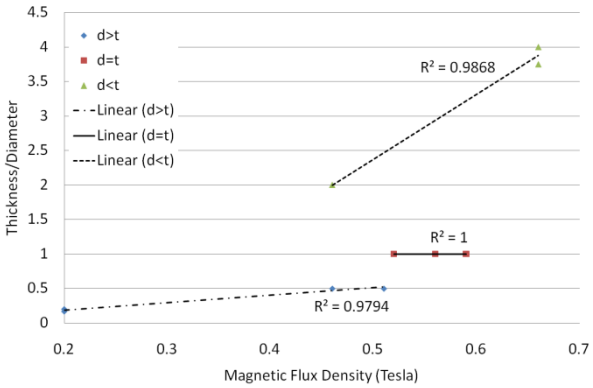

Figure 5. Analysis of the crossing points between the real and theoretical data from all the magnets. Plot Thickness/Diameter against Magnetic Flux Density.

Analysis of crossing points between the theoretical and real world data, when plotted against magnetic flux density, for all magnets (Fig. 5) shows a strong correlation of results between magnets that have proportional dimensions. The trend lines generated show how closely they fit the data and are assigned to magnets with similar proportions.

5. PROTOTYPE DUAL-MAGNET COMPLIANCE UNIT

5.1. Design and Development of the DMCU

The design of the prototype Dual-Magnet Magnetic Compliance Unit (referred to as the DMCU from here on) was based on the initial magnet testing and included two of the ID54 N42 Neodymium magnets. The choice to use these specifications of magnets was so that at a resting state the magnets had a separation of 50mm and could take a maximum of 10kg load at full compression. This would allow a robot with 4 of the compliance units to support a 10kg payload whilst keeping a 4 times safety factor in case of a large impact.

Figure 6. The prototype Dual-Magnet Magnetic Compliance Unit (DMCU). The bottom magnet is visible and the DMCU is held together with brass locating nuts, which will be replaced with nylon bolts in the final implementation of the suspension.

To avoid disturbances to the magnetic field, clear acrylic plastic was used in conjunction with Delrin, as these materials satisfied all the design constraints whilst not affecting the magnetic field.

The clear acrylic plastic also enabled real time video analysis of the system as the Delrin magnet holders could be clearly seen through the casing. The magnets were mounted inside the end of a Delrin rod (Fig. 6), which runs inside the acrylic tubing.

Delrin was chosen as it has a low friction coefficient when used in conjunction with acrylic and is simple to form into usable shapes. The DMCU locks the motion of the Delrin runner to the z-axis only, for simple modelling as well as keeping the operation of the device as accurate as possible. The acrylic tube had a locating slot milled into the sides which stopped the suspension from twisting during operation, so that when wheels are mounted to the bottom they do not rotate around the z-axis.

5.2. DMCU Robot Test Rig

A simple 4-wheeled test rig which incorporates 4 compliance units was also designed to use 4 of the DMCU modules (Fig. 7). The test rig allows each leg to be adjusted so that the angle of attack can be locked between $\pm 45^{o}$ from vertical, as it is rare to have the wheels mounted directly below the chassis, whilst measuring response to terrain profiles.

Figure 7. The DMCU Robot Test Rig with 4 of the DMCU modules attached.

This testing rig is currently being upgraded with accurate electronic sensing equipment so that more detailed analysis of system response can be performed as well as instrumented wheels for feedback of motion as the rover is run over a set of predefined testing environments. The final upgraded test rig will replace the brass locating nuts and the tilting axle with nylon bolts so that the magnetic fields are not affected during testing. Once the upgrades to the DMCU Robot Test Rig are complete, a range of tests will be performed.

These will range from simple drop tests, to see how the system would respond to a simulated planetary landing to driving over pre-defined terrain profiles, which would test how accurate the system model is compared to the real world responses. The electronics that are currently being integrated into the DMCU Robot Test Rig will enable real-time monitoring and recording of the robots motion with respects to the start position, using sensor fusion between a 3axis accelerometer and a 3 axis gyroscope which can be polled at 1kHz and above. This will enable a range of testing data to be analysed and will give a benchmark for further experimentation as well as giving real-time feedback to a visual display. These experiments will provide data which when analysed will aid in the future expansion and development of the DMCU principles for application to space rover suspension systems, specifically the Rocker-Bogie which was described in Section 2.

6. CONCLUSION

The speed a rover can traverse difficult terrain is currently an important research area. In this paper we have considered a number of issues which are concerned with speed of traversal. The paper proposes an approach to rover suspension based on magnetic compliance. The modelling, design and development of a Dual-Magnet Magnetic Compliance Unit (DMCU) was described. Further research will investigate enhancements to the mathematical models and will experimentally evaluate the DMCU using a novel test rig that is under development. Our conclusion, based on our initial observations of the DMCU Robot Test Rig is that magnetic compliance can indeed enhance the versatility of space robotic rovers.

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Figure 1. Courtsey of NASA/JPL-Caltech, Image URL: http://marsrover.nasa.gov/gallery/spacecraft/images/mer2002_1106_b231.jpg