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EXPLORING TITAN'S BIOCHEMISTRY THROUGH THE USE OF AN INNOVATIVE SPHERICAL ROVER

Berent, Sara & Gordon, Robert

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ABSTRACT

Planetary rovers are expanding the horizons of our understanding and knowledge of space. They allow us to reach further into the universe to conduct deep-space exploration missions and investigate the biological, meteorological and geological properties of distant destinations. This article combines a novel conceptual design of a spherical planetary rover, the Armadillo Rover, with a literature review of its investigative capabilities and their scientific potential. Saturn's largest moon, Titan, is used as a theoretical mission destination in this paper, due to evidence for its incredibly potent organic chemistry and unexplained atmospheric events that, upon closer examination, might reveal signs of extra-terrestrial life.

The Armadillo Rover contains many of the highly desirable qualities associated with space system design, such as being light weight, robust and energy efficient, and at the same time enabling execution of biochemical and geological research goals set for standard exploration missions. The solutions implemented in this design should be understood as concepts for universal deep-space exploration, with Titan being used as an example through which the abilities of the Armadillo Rover are visualised. This review highlights the importance of deep-space exploration for understanding science on Earth. It also suggests an example of technology suitable for fulfilling the agenda designed by space agencies for the upcoming decade, with the hope that it will one day serve as an inspiration for designing innovative robotic solutions for deep-space exploration missions.

INTRODUCTION

Space sector overview

Increased investments in space programmes result in innovation-driven applications and benefits such as new devices and services, which are now a coherent part of the global market. It was with the use of the first satellites that we acquired the critical knowledge and capabilities for development of telecommunications, weather forecasting and the global positioning system (GPS). Human activity in space has produced an impressive record of societal and scientific benefits, and the space sector consistently stands out as one of the fastest growing industries in the world. As of 2017, it generated an annual turnover of £31.8 billion in the UK alone, directly employing over 120,000 people and a further 118,000 indirectly (Brien and Rhodes, 2017). It is now that we witness the beginning of a completely new chapter of space exploration, commonly described as the Space 4.0 era, which will require new means of fulfilling our scientific agenda. Future space exploration will focus on sending humans and robots beyond Low Earth Orbit (LEO), subsequently establishing easier access to space destinations such as the Moon, Mars or asteroids (International Space Exploration Coordination Group, 2013). The space industry is noticeably shifting from a state of governmental preserve into a new age of private companies, commercial participation, digitalisation and technological innovation, with the aim of developing easier, cheaper and faster access to space. The establishment of the Space 4.0 agenda for Europe aims to drive the expansion of, and diversify, the space industry, allowing for the invention of new technologies and the creation of new collaborations to further enhance our understanding of the universe. New space exploration mission profiles will allow us to increase our extra-terrestrial presence and redefine space as a place for not only scientific investigation, but in the near future, as an open platform for other business sectors, including asteroid mining, communication via satellite constellations and colonisation of other planets.

Reach into space, and the development of appropriate technology, play a big part in fulfilling the Space 4.0 agenda. This article suggests a novel design of a spherical planetary rover, which would suit a deep-space exploration mission and would allow for effective meteorological, biological and geological characterisation of the destination. Saturn's moon Titan is an interesting candidate for such a mission due to evidence for its incredibly potent organic chemistry and unexplained atmospheric events that upon closer examination might reveal signs of extra-terrestrial life.

Planetary exploration

One might typically associate space exploration with human missions, however, robotic exploration plays and will continue to play a vital role in complementing and supporting these missions in the future. Satellite surveillance, space probes and planetary rovers constitute a group of key tools which support human crews in space and allow us to reach further into the universe to investigate the composition, structure and surface

Sara Berent, Immunology, College of Medical, Veterinary & Life Sciences, 2176088B@student.gla.ac.uk
Robert Gordon, Aerospace Systems Engineering, College of Science and Engineering, 2198304G@student.gla.ac.uk

of astronomical objects within our Solar System. The first remote-controlled robot to land on any celestial body was the Soviet Lunokhod 1 Rover in 1970 and it marked the beginning of a new scientific era; it became possible to explore parts of space beyond the human reach. Since that moment, by means of robotic technology, we have successfully landed on and obtained intelligible data from the surfaces of Venus, Mars, Saturn's moon Titan, the Eros and Itokawa asteroids and the Churyumov-Gerasimenko comet (The Planetary Society, n.d).

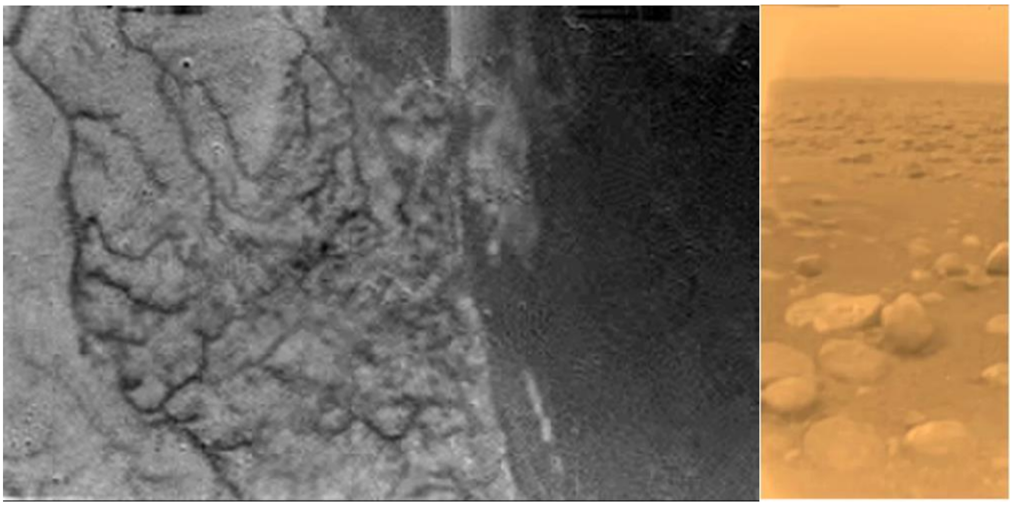

Figure 1: Images of Titan's Surface from the Huygens probe. (Left) image captured during descent onto Titan on Jan. 14, 2005 taken from an altitude of 16.2 kilometres with a resolution of approximately 40 metres per pixel, it shows short, branched drainage channels leading to a 'shoreline' of what is suspected to be a methane lake. Credit: ESA/NASA/JPL/University of Arizona. (Right) image taken after touch down on surface of Titan. The image followed colour processing to add reflection spectra data, which gives a better indication of the actual colour of the surface. Structures visible in the image are most likely rocks or ice blocks. Credit: ESA/NASA/JPL/University of Arizona.

Evolution of rover design

Since the Soviet Lunokhod 1 Rover, the formula for design has not changed much at all. The Curiosity Rover currently exploring the surface of Mars still uses the four wheeled basic design. As the desire to deeply explore our solar system grows the technology of rover design will have to evolve to meet the challenge. Current rover designs are large, slow and cumbersome. They also suffer from their fragility, due to most of their instruments being open to the environment, restricting them from attempting to manoeuvre into certain locations. Future designs will have to be more robust and be able to cover more ground in a shorter period of time. These days, researchers aim to send rovers further into space, but at these distances a high degree of autonomy of rover systems will become one of the crucial requirements for the design of planetary rovers. When exploring destinations that are long distances from Earth, remote control of non-autonomous rovers would contribute to high costs and a long time commitment of tele-operation. Upcoming exploratory missions hence focus on launching systems into space that embrace the ability of adaptation to new event scenarios and autonomous decision-making. Examples of such decisions include diagnosis and prognosis algorithms to maintain vehicle safety and performance upon encountering a problem. After an unexpected impact, a rover with autonomous architecture could determine whether any of its components are failing and could use that information to undertake actions to optimise vehicle maintenance, ensure mission safety, and in consequence, extend mission duration (Narasimhan, et al., 2012).

A number of exploratory missions have been scheduled for 2018, including the NASA InSight mission, launched in May, to measure seismic activity on Mars and determine the planets internal structure. Also launched in 2018 is the orbiter component for the Chinese lunar exploration mission Chang'e 4, with the lander and rover launches planned for December. The Chang'e 4 mission plans to be the first to land on the dark side of the moon, almost 60 years after the first images of the moon's far side were captured by the Soviet Luna 3 in 1959. The dark side of the moon is said to be 'quiet' due to the little electromagnetic interference from the Earth that is thought to reach there. The Chang'e 4 mission will investigate the levels of electromagnetic interference and determine whether the dark side of the moon would make a good location for future astronomical observation equipment, which is sensitive to electromagnetic interference. Later this year two probes that will land on and return asteroid samples back to Earth will be approaching their destinations. The Japanese Hayabusa 2 and NASA OSIRIS-REx will bring back the first asteroid samples to Earth by 2020 and 2023, respectively, allowing us to further investigate the formation of our solar system.

RESEARCH ON TITAN

Titan as a destination

The selection of Titan as the example site is in response to a survey conducted in 2013, which has placed the exploration of Titan's chemistry as a high priority for future missions. Evidence exists for Titan's potent organic chemistry and unexplained atmospheric events that consume hydrogen, acetylene and ethane, all of which are reported to continually descend from the atmosphere, but show no signs of accumulation (Maltagliati, 2017). Understanding what happens on the surface of Titan could change how we interpret, and look for, extra-terrestrial life.

The 1997 Cassini Mission (European Space Agency, 2018) included the landing of the Huygens probe on the surface of Titan, which was designed to gather data in the atmosphere and continued to operate 90 minutes after landing. Thanks to the results of Huygens, we have obtained general knowledge about the surface of Titan, its atmosphere and conditions. The mission revealed Titan's surface to be composed primarily of ice, with geological features such as mountain chains, dunes, cryovolcanoes, large stable hydrocarbon lakes and a few impact craters (Lorenz, et al., 2007). Radar altimetry suggested the terrain had altitude variation of typically no more than 150 metres, however, occasional elevation changes have been discovered with mountains of several hundred metres to more than 1 kilometre in height (Lorenz, et al., 2007; Corlies, et al., 2017). Data gathered from infra-red imaging has also shown the presence of organic chemistry in the atmosphere, which could produce pre-biotic compounds that may give rise to the complex systems and processes we know on Earth. Exploring the surface of Titan is hence crucial to discover sets of biomolecules that could be capable of the same sort of ecological communication and exchange that occurs on Earth. An example of such parallel is hydrocarbon shells, Titan's hypothesized analogue to viruses, which could encase raw Titan genetic polymers.

Life on Titan

The temperatures on Titan are around -180°C, which is too low to support life as we know it on Earth. There is also a lack of oxygen and liquid water which presents further obstacles. Instead, of the oxygen rich environment on Earth, Titan's environment is composed primarily of atmospheric nitrogen and hydrocarbons such as methane, liquid in cryogenic conditions.

All environments are shaped significantly by the polarity of molecules; the difference in electronegativity between the atoms in a bond influences their ability to attract one another or act as a solvent. Earth is a water-dominated planet, which means all life we know has evolved around a polar solvent, properties of which dictate the rules of chemistry and biology. In a world where methane, a non-polar molecule, takes over the role that water plays in our terrestrial ecosystem, life requires completely different conditions, structures and interactions to develop. Hydrophobic molecules such as lipids, owe their ability to form cell membranes, store energy or act as chemical messengers to their insolubility in water. Cells, which are classified as the basic unit of all life, rely on these functions of lipids and hence, up until recently, it was suspected that life can only originate alongside liquid water.

In 2015, Cornell University scientists (Stevenson, Lunine and Clancy, 2015) suggested the possibility of an alternative, nitrogen-based biochemistry on Titan. It contrasts the chemistry that supports life on Earth, but provides the means for formation of cells in methane environments and in spite of the extremely low temperatures. That study described the discovery of azotosomes - flexible, stable lipid structures which use the attraction between polar heads of nitrogen-rich short-chain molecules to form membranes. This process is analogous to the way liposomes, our terrestrial form of lipid vesicles, rely on carbon-rich nonpolar hydrophobic tails and polar hydrophilic heads to adequately function in water.

Furthermore, liquid methane is cold enough to solidify almost any substance, so flexible lipid membranes have always been considered not viable outside of biology based on liquid water. According to the findings, lab-made azotosomes displayed the flexibility of a lipid bilayer even in cryogenic temperatures, which was previously considered impossible. In the experiments on Earth, scientists tested several compounds in their ability to form vesicles under cryogenic conditions. Each azotosome began the simulation as a grid of molecules that would self-assemble into a preferred structure and result in a new kind of cell. An acrylonitrile structure, shown to be present on the surface of Titan at concentration of 10ppm, was highlighted by the study as the most plausible azotosome component. Acrylonitrile cells displayed good thermodynamic stability, high energy barrier to decomposition and responses to mechanical stress similar to that of lipid membranes on Earth. This discovery does not by itself demonstrate that life without water is possible; however, it opened the scientific community to the search for alternative metabolic chemistries that would be similarly compatible under cryogenic conditions. Landing on Titan's surface could answer our questions about the presence of azotosomes and potentially prove the concept of alternative forms of life.

Research aims

We are looking to discover signalling molecules, possibly in the form of low-molecular weight hydrocarbons that could be mobile. Analysis of the nature of these molecules and their relative abundance could suggest a biological signal. This would be of great interest, both as an indication of the presence of a biological system and as an inventory of the molecules used in the biochemistry of that system.

Data collected by the Huygens Probe suggest that the sunlight reaching Titan's surface fluctuates at a level of 0.1-1% of the light that reaches Earth. However, the distribution of solar flux with wavelength roughly follows the solar spectrum, with the peak flux occurring at about 600nm. Such low-light level is more than adequate for photosynthesis on Earth and, hence, suggests photosynthesis on Titan should be possible with pigments not dissimilar to those on Earth (T.Owens, et al., 1997). It is possible that on Titan photosynthesis could produce organic material from CH_4, where H_2 would be a by-product (McKay, 2016).

Long-term land exploration may also reveal new facts about Titan's atmospheric cycles. The moon's climate could contribute to the understanding of the evolutionary processes that shaped our Earth's atmosphere (Corlies, et al., 2017), and hence provide us with data that could be scalable to meteorological phenomena occurring on Earth. The RADAR instrument on the Cassini orbiter collected data that showed plenty of geological and meteorological similarities between Titan and early Earth, including volcanic activity, dunes formed by cold winds, or mountain ranges (Space.com, 2009).

If life indeed exists on Titan's surface using hydrocarbons as a solvent, it is likely to use more complex hydrocarbons as an energy source by reacting them with hydrogen, reducing ethane and acetylene to methane (T.Owens, et al., 1997). This hypothesis was created by astrobiologist Chris McKay and was supported by Darrell Strobel in 2010. His study has shown a greater abundance of molecular hydrogen in the upper atmospheric layers of Titan, compared to the lower layers, and disappearance of hydrogen near Titan's surface. This phenomenon could find explanation in methanogenic life-forms present on the surface (T.Owens, et al., 1997). However, alternative explanations for these findings include unidentified physical or chemical processes, or flaws in the current models of material flow (Lorenz, 2000). Even the sole identification of a non-biological catalyst enabling acetylene to react with hydrogen, still effective at -180°C, would be a ground-breaking discovery (Coustenis, 2005).

THE ARMADILLO ROVER

Design considerations

Biomimetics

Taking inspiration from nature, biomimetics is a form of design that can be applied in space robotics in the context of materials, structures, sensors, mechanisms, behaviour or control mechanisms. It has proved particularly useful in engineering due to the understanding that many biological organisms face the same, or similar, challenges to engineering systems. Despite there being no known species that evolved specifically for the conditions of space, many representatives of our Earth's biological world exhibit qualities that are highly desirable in space system design, such as high adaptability, light weight, robustness, strength or the ability to self-repair (2007 IEEE International Conference, 2007).

Furthermore, it is speculated that terrestrial adaptations and biomimetic solutions can be used for new applications and exhibit increased effectiveness in environments characteristic of space. For example, the properties of the Martian atmosphere could allow for the use of tumbleweed-inspired passively propelled rovers, or insect-inspired flapping flight drones.

In order to meet the need for more innovative rover designs to help widen the scope of future space exploration missions, we have designed the 'Armadillo Rover'. The illustration in Figure 2 depicts the new "Armadillo Rover" design with an inner and outer shell, with the mass of the internal components represented in red.

Figure 2: Armadillo Rover Visualisation

Biomimicry solutions increase the success of long distance missions, which is largely dependent on the reliability of planetary exploration tools. Such designs mimic evolutionary adaptations of animals and aim to increase system robustness by limiting the risk of immobilisation or damage to the rover. The three-banded armadillo curls into a ball, protected by a keratin shell with bimodal size scales which can lock the animal into a perfect, inaccessible sphere with full manoeuvrability. These properties serve as a defence mechanism against attacks of a predator, facilitate the animal's escape and save it from immobilisation. These properties inspired the design presented in this paper, "Armadillo Rover", named after its jagged shell and the ability to exist in both spherical and non-spherical shape.

Spherical design

The analysis of an innovative spherical rover design was carried out to give us results regarding the effectiveness and potential benefits of the altered form of the rover. We argue that the spherical shape will increase the chances of the success of the mission by preventing steering errors from causing issues, and enhancing the durability of the system in such unexplored and difficult conditions as the surface of Titan.

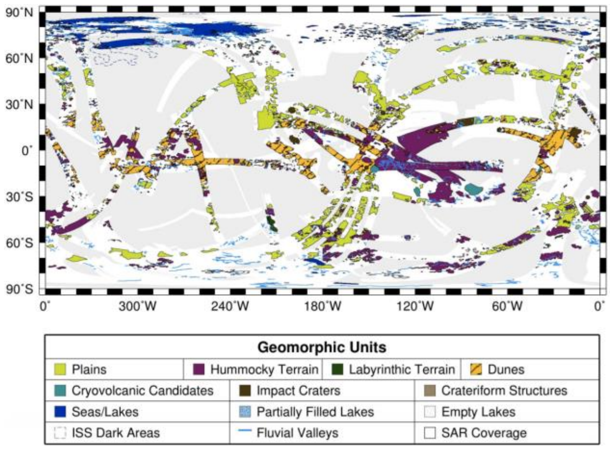

Figure 3: Geology of Titan's Surface (Aharonson, et al., n.d)

The Armadillo Rover's main difference to previous extra-terrestrial rovers is its spherical profile. This smoother, uniform shape prevents the rover from easily becoming stuck on surface features such as rocks, boulders or uneven terrain, which in turn allows for exploration of more treacherous areas of the surface of Titan. In Figure 3 the geology of Titan can be seen, with areas of its surface characterised, showing the wide variety of terrain a rover sent to Titan would have to endure. Another advantage of the spherical design is that the rover has essentially no turning circle, meaning that it is able to traverse in any direction from a stationary position; no U-turns are required. This, again, allows the exploratory rover to access previously inaccessible areas, such as a maze of boulders. Even if the spherical rover were to collide with such obstacles, its design is more robust in that the energy from any impacts could be dissipated over the spherical surface. This would also be highly beneficial in the circumstance that the surface features of a Titan are not fully known.

To ensure that the Armadillo Rover is capable of traversing a gradient, it has to have a centre of mass positioned vertically above the contact point with the ground. This would mean that the rover would have to be able to shift its centre of mass through a mechanism that allows for different gradients to be traversed. Also, if the centre of mass is in front of this contact point then the rover will begin to roll up the gradient due to the moment (torque or rotational force) created by the position of the centre of mass. A mechanism allowing for the movement of internal mass in order to shift the rover's centre of mass, therefore, facilitates the movement and stability of the rover.

The design consists of two concentric spherical shells: the outside shell makes contact with the surface and absorbs any impacts, and the inner shell contains the internal components of the rover such as battery, navigational and communication systems, as well as the experimental instruments needed to analyse the rover's surroundings.

Mathematical modelling

The internal components will constitute a large proportion of the overall mass of the rover and will be compact and placed relatively low inside the inner shell. This will keep the centre of gravity of the entire rover low to the ground. Not only does this help with the overall stability of the rover it also allows for the centre of gravity to be displaced horizontally simply by rotation of the inner shell.

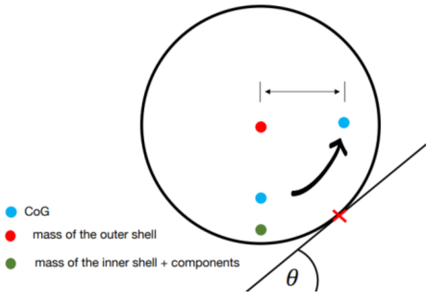

Figure 4: Rover point mass positions

Mathematical modelling in MATLAB was conducted to determine the maximum gradient the rover would be able to traverse. This was based upon the position of the centre of gravity and, therefore, the contact point between the rover and the ground, as seen in Figure 4.

Calculations were carried out with the assumption that the total mass of the rover would be 320kg and the diameter set to 1m, comparable to the Huygens probe previously landed on Titan (mass = 319kg, diameter 1.3m). The analysis was simplified by considering the rover to be two-dimensional instead of three-dimensional. This meant that we were essentially considering the rover only moving in one dimension. The rover is spherical and symmetrical no matter the direction of travel, therefore, this simplified analysis will be applicable to the three-dimensional spherical rover we are designing.

The mathematical model that was created to analyse the rover design simplified the mass of the outer shell (the surface that makes contact with the ground), and the mass of the inner shell, and the components it contains, into two discrete point masses, as seen in Figure 4. These two point masses are then used to calculate the position of the centre of gravity, the average point of both masses R_{CoG}, using equation 1.

$$R_{CoG} = \frac{\sum Moments}{Total\ Mass} \qquad (1)$$

The moments are calculated from the centre of the circle and, therefore, the resultant value from the calculation in equation 1 is the distance from the centre of the circle to the centre of gravity. In order to complete the mathematical model, the positions of the two discrete point masses must be known.

$$\sum M_{@center} = mgr \int_0^{2\pi} \left[\int_0^{\pi} \cos(\theta)\, d\theta \right] d\phi = mgr \int_0^{2\pi} [0] d\phi = 0 \qquad (2)$$

equation 2 shows the integrals for the total moment ($M_{@center}$), at the centre of the outer sphere where m is the total mass of the outer sphere, g the acceleration due to gravity, r is the radius of the sphere, and ϕ are the spherical polar and azimuth angular coordinates respectively. The spherical coordinate system used can be seen more clearly in Figure 5.

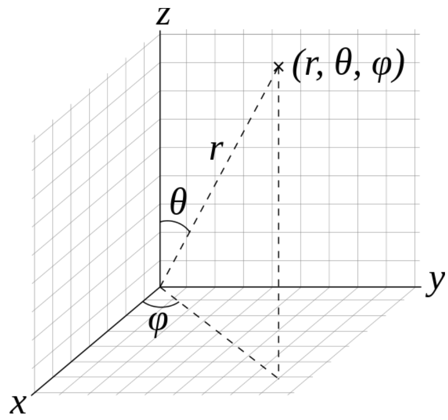

Figure 5: Spherical Coordinate System

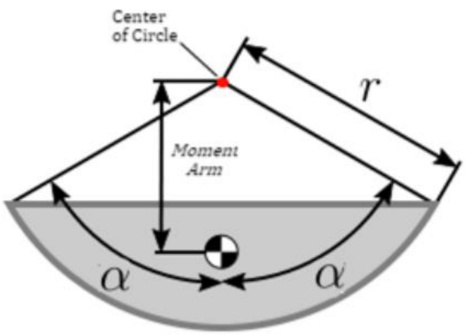

Figure 6: Centroid of Circle Segment

Since the moment at the centre of the outer sphere is 0 we can simplify the mass to be a discrete point mass positioned at its centre Therefore, in our simplified 2D mathematical model we can now consider the mass of the outer shell to be positioned at the centre of a circle. Using discrete masses will make calculations of the total moment much easier. The position of the point mass of the inner shell and its components are determined by considering the centroid of the segment of a circle, as seen in Figure 6. Since the total diameter is set at 1m, the diameter of the inner shell was assumed to be 0.9m, leaving 10cm for the rotational mechanism between the two shells.

$$R_{Seg(CoM)} = \frac{4r\sin(\alpha)}{3(2\alpha - \sin(2\alpha))} \qquad (3)$$

The position of the centre of mass (CoM) of the circle segment ($R_{Seg(CoM)}$) is determined by equation 3 and is proportional to the radius of the circle of which this segment lies within (r) and the angle (α) which is the mass distribution angle for the internal components of the rover seen in Figure 6. The position of the rover's centre of gravity is therefore determined by setting values for (α), and by determining the mass of the outer shell and the inner shell (and components) as a proportion of the total mass of the rover. The radius, r, in equation 3 is also set to 0.45m as previously mentioned.

$$\theta_{max} = \cos^{-1}\left(\frac{R_{CoG}}{r}\right) \qquad (4)$$

Assuming that the rover can rotate its inner shell so that position of the centre of gravity ($\boldsymbol{CoG}$) from the centre of the rover is purely horizontal (Figure 4), the maximum gradient, $\boldsymbol{\theta_{max}}$, that the rover can traverse (ignoring frictional considerations) can be determined using equation 4 which can be derived from Figure 4. It would be expected that the greater the mass of the internal components the lower the overall $\boldsymbol{CoG}$ of the rover will be. And since, in the design, the $\boldsymbol{CoG}$ can be rotated, a lower $\boldsymbol{CoG}$ will result in a greater maximum traversable gradient.

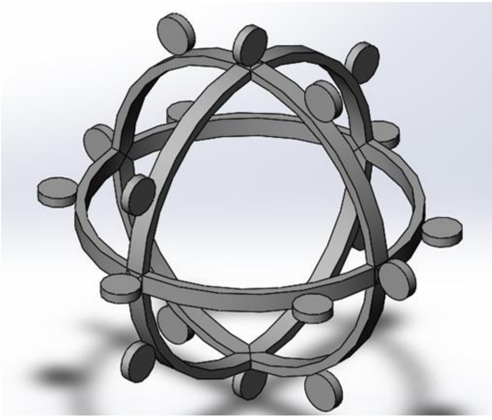

Figure 7: 3 axis wheel system

However, if the internal components are distributed over a large volume (area in our 2D model) then this would cause the $\boldsymbol{CoG}$ to be higher, as less of the mass is positioned directly below the centre of the rover. Therefore a lower α value, more dense distribution of internal components, should result in the $\boldsymbol{CoG}$ being lower and, therefore, increase the maximum gradient.

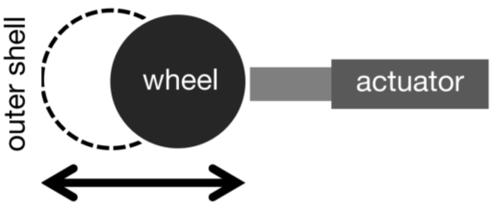

Figure 8: Wheel actuator system

Three sets of wheels are attached to the inner shell of the rover and make frictional contact with the outer shell. This mechanism allows the inner shell to rotate in all three axes of rotation inside the outer shell and cause displacement of the internal mass and the centre of gravity. Each set of wheels allows rotation in one of the three axes and will have separate actuators allowing for the wheels to be engaged, and disengaged, from contact with the outer shell. This will allow for any orientation to be achieved through rotation of each axis sequentially.

Equipment.

In order to successfully fulfil the goals of a deep-exploration mission, it is necessary for our rover to be equipped with navigation tools, including a visual aid in the form of a camera, as well as planetary characterisation tools for meteorological and chemical analysis. The instruments that would constitute these internal components are:

Infra-red camera. Due to Titan's distance from the sun (10 AU) and its thick atmosphere, the maximum level of sunlight on the surface of Titan is about 0.1-1% that of the overhead sun on Earth's surface (data collected from Huygens Probe). Such low visibility would constitute a major obstacle if a regular camera were used for navigation. Using an infra-red camera would provide support for hazard identification and digital terrain modelling to help guide the rover during exploration activities. It could furthermore help assess the high-resolution morphology, topography, and geologic nature of Titan's surface (Bell, et al., 2003).

ORBITRAP mass spectrometer and *gas chromatographer*. This device allows for different ions to be deflected by a magnetic field; the amount of deflection can be used to identify and differentiate between ions. It is designed to fit within a standard 43cm diameter Benthos glass pressure sphere, with the battery in the lower hemisphere. This will be one of the most important instruments on board the Armadillo Rover, as it will allow for the verification of the chemistry hypothesis. One of the biggest advantages of ORBITRAP are its incredibly low power requirements (less than 20W in continuous operations mode and as low as 2W when the filament and scanning circuitry are not in use (Baldwin, et al., 2016)).

A *robotic arm* with a small drill and a vacuum tunnel in the centre as well as heating panels located on the 'fingers' will help in preparation and transport of samples into the ORBITRAP. Its main functionality lies in arm's ability to extend, bend, and angle precisely against the ice on Titan's surface, to further adequately prepare and transport the examined material into the spectrometer chamber to analyse its elemental composition. The arm could be further equipped with a microscopic imager to provide close-up views of surface materials and produce microscopic images of potential biological structures found on Titan's surface.

Meteorology and physical properties package (MP3), standard rover equipment will help us explore the mysteries of Titan's climate, methane cycle and may give us clues about the evolution of early Earth itself. A MP3 is an integrated suite of small, simple sensors that combines the function of traditional meteorology packages with the analysis of physical properties and composition of liquids. Such equipment provides us with the opportunity to coherently analyse the atmospheric cycle on Titan using meteorology sensors exposed to the atmosphere; a pressure sensor, a seismometer, ultrasonic transducers for the detection of wind and diode thermometers for temperature measurement will conduct the first long-duration in-situ monitoring of conditions on Titan. This will allow us to construct a model for Titan's circulation of compounds (Lorenz, et al., 2012). Additional sensors (for example, ultrasound transducers) could be introduced to the package to allow for detection of heterogeneities in Titan's composition, such as methane-rich rain layers (Arvelo and Lorenz, 2013).

Chamber with nanoparticles. Nanoparticles, if dispersed in liquid methane, would not be influenced by cryogenic conditions and would provide us with various research opportunities. Depending on the desired research goals, Armadillo Rover could be equipped with nanoparticles of magnetic, targeted or fluorescent nature, in various shapes and sizes. Nanomaterials constitute a group of incredibly efficient diagnostic tools and multiple nanostructures have already been used to detect chosen molecular targets in biodiagnostic applications on Earth. Even the slightest modifications to the nano-surface can induce dramatic alterations in some of particle properties, which allows even for single binding event to be potentially recorded (Kaittanis, Santra and Perez, 2010). Programmed to target amino acid sequences or particular elements of the cell, they would help us identify the parallels between the biology found on Earth and Titan.

All of the electronic devices suggested above are suitable for use on Titan due to their low power consumption, limited weight and size. These characteristics will allow the rover to operate for longer and would not interfere with its ability to climb inclined surfaces, as opposed to heavier and more energy consuming items. They comprise all the tools necessary to fulfil the biochemical and geological research goals suggested for a long-term exploratory mission to Titan.

Mission design

As the probe will orbit the moon, it will gather current information about the topography of the surface – which will let us update and detail the map of Titan. If any changes in the topography are observed, it will give as an idea of the presence of unexamined seismic and geological processes. Climate modelling subsequent to the landing of the Huygens probe showed that Titan's global circulation disfavours the accumulation of liquid hydrocarbon at the equator, where the landing site should be. A seismometer installed in the rover will be able to confirm or contradict our hypotheses during land exploration. This analysis could also let us come closer to finding out the structure of the crust of Titan. At the same time, the tools for chemical analysis will allow us to create a database of organic compounds abundant on the surface of Titan and their characterisation. This creates the possibility of identifying a new kind of biochemistry based on nitrogen.

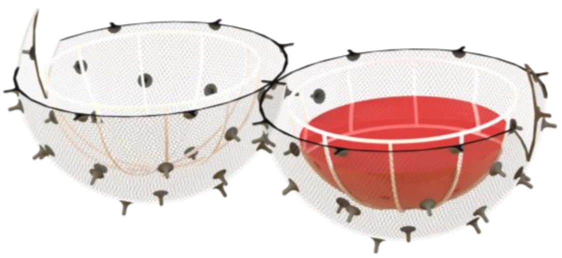

Figure 9: Opening Mechanism

The rover will also require some sort of opening mechanism allowing for the experimental equipment access to the environment. This could be done in several ways, the simplest of which would be to have the whole rover open on a hinge with the rover splitting into two hemispheres. The other option may be to have smaller access ports on the surface of the rover allowing access for the rover's experimental tools. However, this might require the rover to first roll into a particular orientation depending on where the access port is on the rover's surface and making sure that the inner and outer shells line up correctly to allow the desired tool access. To simplify our design we opted for the hinged opening mechanism seen in Figure 9.

Results and discussion

Using the mathematical model with different parameters allowed for different aspects of the "Armadillo Rover" theoretical performance to be explored.

Maximum traversable gradient

The first aspect that was explored is the relationship between the proportion of mass in the inner shell and the maximum transverse gradient. The mathematical modelling was conducted with mass distribution angles of the internal components (α) of 10, 60 and 90 degrees. The plots for all three cases can be seen in Figure 10.

As can be seen in Figure 10, a higher proportion of mass in the inner shell results in a steeper maximum gradient for the rover. This is to be expected as the mass with the inner shell is the mass that will be displaced to shift the centre of gravity. The more mass that is displaced, the greater the displacement of the centre of gravity and, thus, a steeper maximum gradient is possible. The gradients achievable by this rover are very comparable to that of conventional four wheeled rovers with the maximum gradient performed by the Curiosity Rover being 32 degrees.

The second aspect to be explored is how the distribution of the internal components affects the maximum gradient traversable by the rover. The distribution of the internal components (α) is varied to give different values of θ. The results of setting the mass of the internal components to 50% of the total mass and varying α from 0 to 90 degrees can be seen in Figure 11.

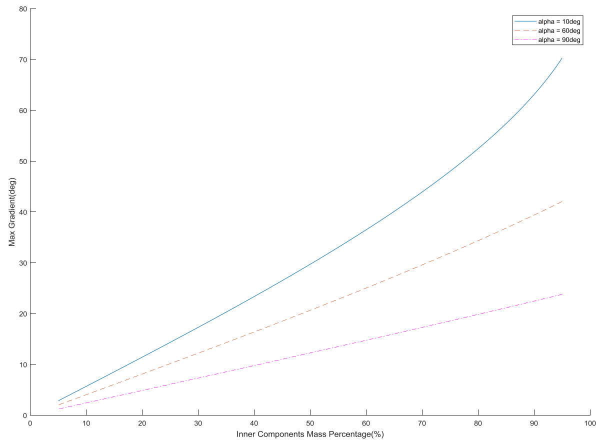

Figure 10: Inner Component Mass Percentage vs Maximum Gradient for different Alpha Values

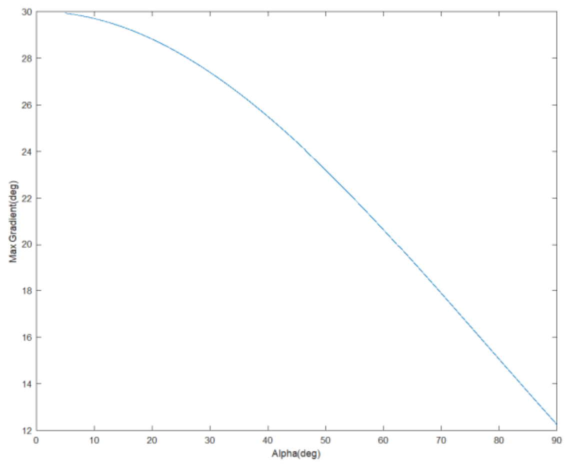

Figure 11: Alpha of segment vs Maximum Gradient

It can be seen from Figure 11 that as the α value decreases, the maximum traversable gradient increases. This was expected as a smaller angle α essentially means that the internal mass, or components, of the rover and more densely packed causing the point mass to be lower within the inner shell. Since the point mass is lower, it has a greater influence on the centre of mass when the inner shell is rotated due to the mass being concentrated farther from the centre of the spherical rover. So, in order to maximise the gradient that the rover can traverse, the internal components of the rover needed to be compact and constitute a high percentage of the overall mass of the rover. A significant design consideration is to build the rest of the rover to be as light as possible. Material choice will still have to be robust enough for the impacts expected upon landing on the explored planetary body, and durable enough to last the length of the mission.

Design limitations

There are limitations to how much mass can be concentrated inside the inner shell and how concentrated the mass can be (i.e. how small angle α can be). Factors limiting how compact the internal components are include technological geometric limitations. Some components, such as batteries, will take up a large volume. Also, another important limitation is that the more compact the inner components, the more difficult it will be to deal with waste heat from the electrical components. Dissipating heat can be a major problem in environments with low atmospheric densities or near vacuums or indeed complete vacuums. This is due to the limited effect of convection and conduction in dissipating waste heat away from the spacecraft or, in this case, the rover.

Another limitation of the design that was not explored in the MATLAB mathematical modelling conducted was the issue of friction. For the rover to function as intended the outer shell needs to have enough friction with the ground so that no slipping occurs at the contact point when the rover begins to rotate. The three sets of wheels attached to the inner shell also need to have sufficient friction with the outer shell to prevent slipping and facilitate the rotation of the inner shell.

Surface features on the outer shell such as spikes could add more grip and friction between the ground and the outer shell of the rover helping to prevent slipping at the contact point. If the spikes were made from a flexible material such as rubber, then this would help impact absorption and durability of the rover. For the wheels inside the rover making contact with the outer shell, an interlocking meshing between the wheels and the inner surface of the outer shell could be used to greatly increase friction. This will also aid the inner shell in maintaining its desired orientation.

Conducting research with Armadillo Rover

The above analysis proves that the novel spherical shape of the rover would suit a long-distance planetary mission, by increasing versatility and enhancing the durability of the system in difficult navigation conditions. In the case of autonomous decision architecture, such design would provide plenty of room for the system to learn and respond better to new scenarios, as the rover's closed shell structure limits potential damage to any of the internal elements. The Armadillo Rover comprises some of the highly desirable qualities in space system design, while at the same time allowing for executing biochemical and geological research goals set for standard exploration missions. The instruments present on board of the rover allow for characterisation of planetary body's climate, surface composition and detection of even highly specific compounds, with minimum energy consumption and weight which not only allows for, but supports climbing inclined surfaces due to a clever mass-shifting solution.

This article focuses on the benefits of an exploration mission to Saturn's moon Titan due to numerous scientific benefits that such investigation could bring. With the potential discovery of alternative biochemistry on the surface of Titan, we will not need to associate life with water anymore. The importance of Titan in this connection is that it may preserve, in deep-freeze, many of the chemical compounds that preceded life on Earth. Some scientists believe we will find that Titan shares more in common with early Earth than Earth itself does today. Exploration of Titan will hence carry information just as crucial for understanding our past, as for shaping our future.

However, the solutions implemented in this design should be understood as concepts for universal deep-space exploration, with Titan being used as an example solely visualising the abilities of Armadillo Rover. The equipment suggested for a Titan mission comprises the most basic scientific investigation techniques, which could easily be replaced with more sophisticated tools, such as a full 360°, multispectral panoramic camera, depending on the destination of the mission (Bell, et al., 2003). In the case of Titan, limited sunlight on its surface made it impossible to use solar panels as a charging source for rover's battery and constrained the amount of energy that could be lost to rover's payload. However, at a different destination, where solar or wind forms of re-charging would be available, such a rover could carry equipment with more energy hungry parameters. This innovative rover design is robust and durable thanks to its protective shell, without suffering from the possibility of tipping over which could bring an early end to the life of a conventional wheeled rover. Its instruments allow for scientific discoveries on the surface of yet unexplored planetary bodies and comprise sustainability with excellent investigation techniques. We believe that the Armadillo Rover is an example of technology suitable for fulfilling the Space 4.0 agenda, and will one day serve as an inspiration for designing innovative robotic solutions for deep-space exploration missions.

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