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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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TABLE OF CONTENTS

INTRODUCTION

Human beings are naturally inquisitive creatures, and the mysteries of space and other heavenly bodies have for ages held men in awe. For early astronomers like Galileo and astronauts and scientists of today, planetary bodies hold a vast amount of information which could provide answers to questions which have plagued both the academia and human beings in general for a long time. Questions like what the shape of the Earth is, does life exist outside Earth and how the universe was formed, are examples of questions which have been answered or are being investigated with the aid of knowledge acquired from outer space. It is this human drive for understanding that has fuelled space exploration and propelled man deeper into the heart of space.

There is an enormous expanse of uncharted space and planets which could hold clues to so many questions, but to get a human to travel to these areas and carry out investigations could take anywhere from a couple of months to a lifetime, and in some cases the environment cannot sustain human life. It is for these and other reasons that robots have been designed and built to carry out exploration that hitherto would have been carried out by humans. These robots are usually referred to as rovers, and have other areas of application outside space exploration. Bomb disposal units and nuclear facilities are other examples of places where rovers are frequently deployed to carry out tasks that could be fatal if an individual had undertaken them. The one thing which differentiates rovers used in space research and rovers used in other fields is the level of autonomy the space rovers have. The distance a rover is from its handlers coupled with other factors like its lifespan determines the level of autonomy and therefore intelligence the rover will have.

There are currently two rovers on the Mars, which have been engaged in research for a year now. Even more recently a probe sent from earth has reached Titan, a moon of Saturn and is investigating its atmosphere. Space agencies around the world are or are in the process of building rovers that would be sent to various planets to conduct one research or another. This report aims to present the progress made so far in rover technology and offer a model which could be used in designing future rovers.

In this report we shall mainly focus on the rovers that are currently being used on Mars and a part of our future rover model will use Mars as a reference, but there is nothing which stops our model from being modified to suit any other planet. In the sections that follow, we shall talk about the different aspects of a rover like artificial intelligence, navigation and communications which are integral parts to their jobs as explorers. In each area of the rover we focus on, we shall briefly describe what obtains now and then propose ideas which could be used in designing future rovers in other to increase their efficiency and maximise the resources available to them. In a later section we shall bring all our ideas together and paint the full picture of our future rover.

OVERVIEW OF FUTURE ROVER SYSTEM

In this report we try to put forward a model of the way we think future rovers should be designed. Rover systems currently being used are designed with only one rover carrying out all the functions. The rover in this case is responsible for generating power for its operations, conducting experiments, processing data collected from these experiments, relaying these results back to Earth and carrying out other functions that are essential for its operation. Although this method is currently yielding positive results, we are of the view that this method can be modified to produce even greater results from any rover system.

We are therefore proposing a rover system that involves several rovers working together in a group. In this setup, one rover known as the mother ship or base station will be equipped with power generation capabilities, data processing ability and greater communication facilities. The mother ship will be supported by three to four smaller rovers. When a potential site for study is located, the mother ship will move with the other rovers to the site and set up base. The sub rovers who will each be able to carry out a specific activity like taking quality scientific pictures, recovering samples for analyses and carrying out chemical testing will then be sent out to carry out their jobs.

The sub rovers will get most of their power from the mother ship, but could be fitted with solar panels to supplement the power they receive from the base station. Also cameras that will aid the rovers carry out their research will be fitted on them, although the rover that is specialised in taking scientific pictures will have cameras of higher resolution mounted on it. Communication to and from Earth will be via the base station, but a back up system will enable an alternative communication to Earth if the base station develops any problems. Also, all the rovers will be linked by a local communication network and instructions can be issued via this network by the mother ship to the sub rovers. In general, the smaller rovers will have some level of autonomy (i.e. data processing, etc), but they will be dependent on the base station for power and greater processing ability.

The base station will house the smaller rovers during the initial landing on the planet. It will also have ports were the rovers can recharge their batteries and upload data that they gather during missions. The mother ship will be mobile and able to navigate the terrain.

Several of these rover systems involving mother ships and sub rovers could be deployed in different locations on a planet and could then be linked by their mother ships. This link between rover systems will increase the chances of having a communication link with Earth, i.e. if a particular mother ship is having problems establishing a link to Earth due its location, it could use nearby base stations to act as a relay to Earth.

In the sections that follow, we will delve deeper into some of the points raised in this overview.

COMMUNICATION

In this section we will be looking at the communication infrastructure that the rover utilizes to carry out its duties. Communication is one of the most essential elements that have to be considered during the design stage; because if the rover loses contact with Earth then any data it acquires cannot be relayed to its operators thus defeating the whole aim of is voyage. At present the rovers on Mars can exchange information with the control station on Earth, but do not have a direct link with each other. In the new system we are putting forward, Mars based vehicles will be able to communicate with each other directly and also with the scientists on Earth. To make this possible, we have to consider different types of networks which will allow for both proximate and long-haul data links.

TYPES OF COMMUNICATION SYSTEMS

The present link system between Mars based vehicles (rovers) and Earth utilizes X-bands and microwave technology at around 85 kilobytes per second. However there are plans by the American space agency; National Aeronautics and Space Administration (NASA), to substantially improve this. According to them 'the aggregate data produced by these missions will be multiplexed through a backbone network to the Earth that will eventually support data rates in the Gigabits per second region'[1]. In NASA's proposal, this Earth – Mars backbone network provides the long distance data link between the rover and Earth based communication infrastructure such as the Deep Space Network (DSN). Other data exchange mechanisms include space agencies intranet, virtual private networks (VPN) and the internet. DSN is currently used by NASA to track its missions and it has three sites on Earth in California, Spain and Australia which support its operation.

To aid their missions, rovers will need to keep in contact with each other and this can be done by establishing wireless links between planetary machines at a relatively close distance. There are different communication architectures which have to be considered when designing the communication network.

- Surface- Surface: This is the network which provides a link between surfaced based vehicles.
- Orbiter- Surface: This network provides a link between vehicles in orbit and on the surface of the planet. The airborne crafts could be configured to act as a relay between Earth and the surface rovers.
- Orbiter-Orbiter: This network will provide a conduit for data between two orbiting space-crafts.

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[1] Advanced Communication Networking Technologies for Mars Exploration, p.1 NASA Glenn Research Centre, Jet Propulsion Laboratory, California Institute of Technology.

Also, the internal architecture of the rover has to be considered, as data paths have to be created which link the different parts of the rover. An internal Local Area Network (LAN) which utilises both serial and parallel buses is currently being used to connect the various modules of the planetary vehicles together.

DATA TRANSMISSION

To aid data transmission to and from Earth, we are proposing a sort of internet which will link most planets and the Earth. The Internet Planetary Network (IPN) will be made up of disconnected internets with each planet acting like a sub-network with its own internet. With NASA having plans to deploy more rovers to Mars in the future, arrangements are being made to create some sort of internet on Mars which will link the planet's computers. If such planetary internets are created for other planets, then the idea of creating an IPN becomes even more feasible.

DATA TRANSMISSION PROTOCOL

Even after all the necessary hardware has been installed, the means of interaction between the various space-crafts will have to be standardised to ensure accurate data transmission and reception, hence a protocol will have to be formulated. To ease the burden of software development, existing protocols like Internet Protocol (IP) or languages such as Java and HTML could be used in the new protocol we are advocating. However, there are still some problems that have to be resolved in order for our network to function effectively. There are issues of long propagation delay times, power attenuation of the signal and possible data loss. If these problems are solved, then a standardised protocol will enable a long lasting network which could be used as a sub-network within an IPN to be established. Currently, with the Mars rovers a standard naming and addressing scheme is emerging from the LAN within the rover. Integrating this existing protocol with a new protocol will create a communication architecture which will allow for easy access of resources.

TECHNOLOGY FOR LONG RANGE COMMUINICATION

A high rate of data transmission is required in order to keep the rover in constant touch with Earth. The X-band frequency which has a relatively low rate of transmission is the current mode of transmission used by space agencies. The Ka- band which can increase the radiated power of the transmitter and also handle a higher rate of bit-stream is a viable alternative to the X-band. Ka-band is the Radio spectrum in the 18 GHz to 31 GHz range used by satellite communications system. We shall now outline the requirements we need to realise the Ka-band of transmission.

In other to operate at Ka-band frequency, we need to properly consider the issue of power amplification. High efficiency Travelling Wave Tube Amplifiers (TWTA) which can operate in the Ka-band and have power ratings of 30W and 100W are used to amplify the power. A TWTA, shown on figure 1, works by modulating the velocity of electrons near the source of the electron by an input signal. The electron beam goes through a wire helix where it is transformed into electromagnetic waves which are then modulated to carry information.

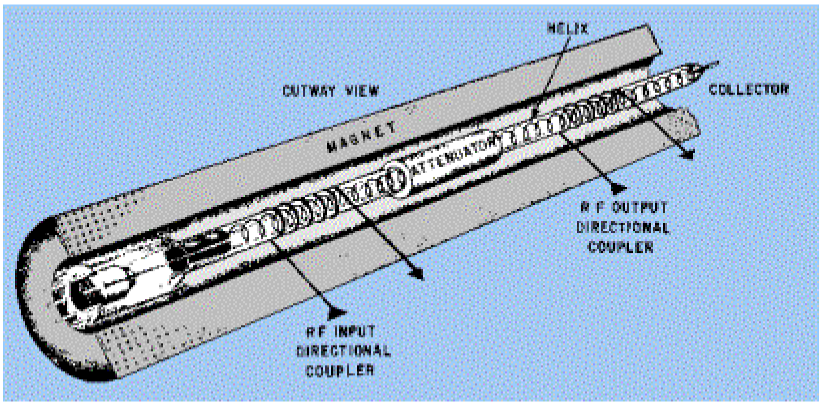


Figure 1 – TWT cross section, showing the helix which is used to generate the high frequency signals

Ultra low noise cooled receivers will be used for the Ka-band based network, because most of the planets where the space vehicles will be used have cold climates. Low noise amplifiers based on high electron mobility transistors (HEMT) which work effectively in cold environments could be used in the receiver to boost the received signal. Plans are already in advanced stages by the Jet Propulsion Laboratory (JPL) a subsidiary of NASA, to develop metamorphic HEMT power MMIC which could be used for a Ka-band solid state amplifier. Also with the recent advancements in Hetero structure materials, MHEMT MMIC amplifiers with a size of 0.1 micron can be made to have an efficiency of about 50%. We must also take into consideration the amount of interference our signals will encounter after transmission and before reception. Since we are transmitting over a long range, we must design a system with a very high Signal to Noise Ratio (SNR).We can get around this problem by using optical based laser telescope to send the signal. According to a paper published by scientists working at the JPL, a laser telescope which utilizes optical technology could be used to 'promise large gains in signal to noise ratio'[2].

Having resolved hardware issues we must now consider what protocol the software operating in the Ka-band will follow. Internet based protocols can be used, as they can support additional capabilities like network switching, firewall protection and temporary storage. Other protocols already exists that can be used for our long range network. Protocols like Near Earth Space Protocol (SCPS-TP) or deep space protocols like File Delivery Protocol (CFDP) may also be used. CFDP was developed by the Consultative Committee for Space Data Systems (CCSDS), to transmit data as a file rather than as a bit-stream and also to eliminate the need for end-to-end communication. This means that not all the transmitted data is required to be received in other to

[2] Advanced Communication Networking Technologies for Mars Exploration, p.5 NASA Glenn Research Centre, Jet Propulsion Laboratory, California Institute of Technology.

recover the sent information, thus making the system robust to interference which may occur in the channel during transmission.

TECHNOLOGY FOR PROXIMITY NETWORKS

Going by plans of space agencies, the amount of space based vehicles (i.e rovers, landers, orbiters, etc) is set to substantially increase in the coming decade. NASA for example has plans to send orbiters and possibly more rovers to Mars in the next few years. There is a need therefore to fashion out a way in which these space vehicles could communicate effectively. A group of rovers could even be made to form a network and work as a team. One member of the team will act like a base station (or mother ship) while the other rovers will be designed to carry out specific task.

An omni-directional radio frequency (RF) system operating in the ultra high frequency (UHF) range can be used to transmit data between an orbiter and a rover or a mother ship. The orbiter could then be configured to act as a relay between Earth and the surface based vehicles. Using the orbiter as a relay will boost the rate and volume of data that can be sent to and from Earth. To take care of any contingencies, a directional antenna system can also be installed on the rover, to provide a path of communication with Earth if the orbiter develops any problems.

For proximate networks between rovers, transmitters and receivers which consume relatively small power and have a small mass, and which can operate in the X-band, Ka-band or UHF frequencies can be used. This proximate network could also be used as a relay by a rover in a group of rovers to send information to Earth via the orbiter.

ARTIFICIAL INTELLIGENCE

Rovers are expected to operate semi independently of human control. They are required to process set instructions and to handle any contingencies that may arise. Some day, the rover will be able to operate totally independently and fashion out its plans and make decisions by itself, but we are still a few decades from such technology. However, we will focus on the type of technology that allows scientists to program a rover to respond to different situations and the rover implements these instructions and has the ability to troubleshoot. There are a few salient points that we must bring into consideration when we design the control of a rover.

- **Flexible operation**; a rover should be able to choose from a list of possible actions, the most appropriate action that suits a given situation.
- **Resource utilization**; resources such as power, data storage and communication bandwidth are limited, the rover needs to be able to manage its resources effectively to give optimal operation. It needs to be able to track actual and expected resources and modify its operations to suit its resources.
- **Failure recovery**; given the complex nature of its operation, rovers should be able to diagnose faults and then try to recover from the faults. It should be able to send records of faults it cannot solve to operators on Earth.
- **Uncertainty**; rovers operate in environments that are not fully understood, it must therefore not be programmed to follow precise instructions, provision should be made for an unforeseen circumstance or factor.
- **Limited communication**; given the time delay and the limited use of the Deep space network, rovers should be able to operate between communication events when no human input can be made.
- **Multiple objectives**; A deployed planetary rover must balance considerations such as science, communication, resource consumption and fault recovery. It must be able to strike a balance between varying tasks.

NEXT GENERATION OF ROVERS

The next generation of rovers will be more flexible, able to execute complex commands, which tell the rover explicitly what to do if something goes wrong. They will execute plans more flexibly so that minor problems such as incorrect resource estimates or motor overheating do not result in complete system failure.

Consider an example of the rover backing up to get close to a rock to perform some tests on the rock. The backing up operation should include the ability to try different routes if its first choice of route becomes impossible to negotiate. The rover should be able to take a moment to let an overheating motor cool down rather than abandoning the entire operation. Certainly the rover should verify the accuracy of its instruments before embanking on hours of measurements. While performing measurements the rover should make sure it has enough energy to send its data back to Earth during the next communication cycle and should be able to stop measurements if it ends up in a shade and cannot generate enough energy to sustain the operation.

INTERACTION WITH THE ENVIROMENT

In the past, MIR (model based mode identification and reconfiguration system) has been used to model systems, such as spacecraft, in which the environment outside the spacecraft can be effectively ignored. Spacecraft follow known trajectories, free of obstacles, in which the external environment can be reduced to a few simple variables, such as the relative position of the Earth. On rovers, interaction with the environment is central to many of the possible faults; dust accumulates on the solar panels, the rover passes into the shadow of large rocks, or it gets caught on small ones. In order to handle failures involving external factors, we need to add the capability to reason from first principles to the rover. We intend to combine the model-based deduction used by MIR with hybrid simulation, to capture factors such as rover kinematics.

ACTIVE SENSING AND TESTING

The sensor information that MI (mode identification) can passively acquire is not always adequate to allow an unambiguous diagnosis, which may make it impossible for MR (mode reconfiguration) to identify the appropriate recovery actions. In general, it may be ambiguous which of two failures has occurred if both are consistent with observations, and it may be ambiguous whether a given component has failed or the sensor responsible for measuring that component has failed. If an encoder indicates that a wheel drive motor is not turning, or is turning too slowly, that could be a sensor error: the encoder may be skipping counts or entirely dead. While MI could look at other evidence, such as motor currents, to see if the motor appears to be stalled or encountering unusually high torque, that evidence may not be sufficient to determine the true fault. If the encoder is giving low readings, the controller, which tries to maintain the desired encoder values, will tend to speed up the motor, resulting in higher wheel currents, which could be taken as evidence of excessive torque. Furthermore, failures such as a motor stall or excessive torque can reflect a number of different underlying faults, such as seized bearings or a rock caught in the wheel. The true state of the rover may be determined by performing experiments designed to eliminate certain candidate diagnoses. For example, if the wheel does not appear to be turning, the rover could try backing up to see if the wheel is caught on a rock. Or it could try driving with some subset of the wheels, and use other sensors to determine if the rover is moving in a manner consistent with the encoder readings. To deal with these ambiguities, we are adding the capability to perform active sensing and testing in order to narrow the candidate situation assessments (diagnoses) and in order to evaluate the utility of alternative recovery plans. In support of this active testing, MIR can make use of its models, both to determine when there are multiple competing diagnosis and to identify activities it can perform that will rule out or confirm certain hypotheses. Reasoning about the information to be gained by executing actions exceeds the ability of the MIR system designed for the Remote Agent, but we are working to provide that capability.

Work in active testing for diagnosis is typically based on probe selection for circuit diagnosis, and it relies on certain simplifying assumptions that are valid for circuits but not for rovers. Some of the key assumptions are:

- Measurements do not affect the state of the system being diagnosed.
- All measurements have equal cost.
- The goal of making measurements is to eliminate ambiguity as quickly as possible (i.e., to minimize the total number of measurements); the order of measurements is otherwise irrelevant.

These assumptions lead to a minimum entropy measure for probe selection. The next probe selected is the one that results in the lowest expected entropy of the probability distribution of diagnoses. This policy tends to minimize the total cost of measurements, under the assumptions listed above. However, these assumptions do not hold in the rover domain, for the following reasons, so minimizing entropy is not sufficient.

- Any information that can be obtained without changing the state of the rover, as long as it is not too expensive to compute, is already continuously available to MI. Any additional tests involve causal action, such as spinning a wheel or taking a picture from a camera.
- On a rover, some sensing actions may have very high cost, including the possibility of causing some undesirable side effects, while others are relatively cheap.
- In the rover autonomy architecture, the main purpose of diagnosis is to disambiguate the rover state enough to find an appropriate recovery plan. Thus, not all ambiguities are equal: the value of information depends on the value of the recovery it supports. In the case of multiple faults, one fault may be more critical and need immediate response, meaning measurements relevant to that fault have priority. If several candidate faults have the same recovery procedure, fully disambiguating the fault may even be unimportant. We are exploring a modification of the minimum-entropy model, which ranks measurements according to the recovery actions they support and penalizes measurements based on the cost of the corresponding sensing actions.

CHEMICAL TESTING

One of the important information which we as human beings want to know from Mars is whether any life exists on Mars. Although it is very unlikely to have human-like creatures, primitive bacterial forms may exist. Therefore, one of the tasks for a Mars rover is to detect these life forms.

VIKING'S FAILURE

Previous rovers such as the 'Viking' carried a Mars Organic Detector (MOD) to collect and analyse samples from Mars to determine whether any life has or had been present on the Martian ground. However, no positive result was found. This may be due to the fact that the sensitivity of the MOD onboard Viking was very low (in the part per billion range)[3]. As a single bacteria only measured around 10^{-16} grams and only 1/3 of that is actually amino acid. Therefore, in 1 gram of soil, the instrument would not be able to measure anything even though there might be a million bacteria cells in it.

MOD IN BERKELEY

In order to improve the sensitivity of the instrument, University of California, Berkeley, is trying to develop a new MOD which can be used in the rover that will be sent to Mars in 2009. The technology advanced from the human genome project, the new MOD aims to measure the amino acid composition and by analysing the ratio of optical isomers present, hence determine whether any life is present. As we all know, one major building block of life is protein and a chemical block for protein is amino acid. There are two optical isomers of amino acids. On earth, living beings only contain one type of amino acid isomer. Therefore, when analysing the chirality of the amino acids we can find a sharp peak at d-isomer amino acids. Likewise when we employ this new technology onto Mars Rovers, we can find out whether life actually exists on Mars by observing either a peak at l-type or d-type isomers.

Furthermore, the device which is being developed in Berkeley is about 1000 times more sensitive than the Viking mission. Therefore, it would be more likely to observe life on Mars if there is any. The results would take around 30 minutes to generate along with the transmission time of the data, the information can reach back to Earth in a relatively short period of time and multiple tests can be performed to confirm the presence or absence of life on Mars.

[3] http://exobio.ucsd.edu/MOD/mission.htm

HOW THE MOD WORKS

For the Viking, the MOD used sublimation to obtain samples of amino acids. A sample is heated up and turned into gaseous form. The gas then sublimes to form amino acid solids on the edge of the 'cold finger' which contains liquid nitrogen. The amino acid solids are then analysed to find out the type of amino acid it contains.

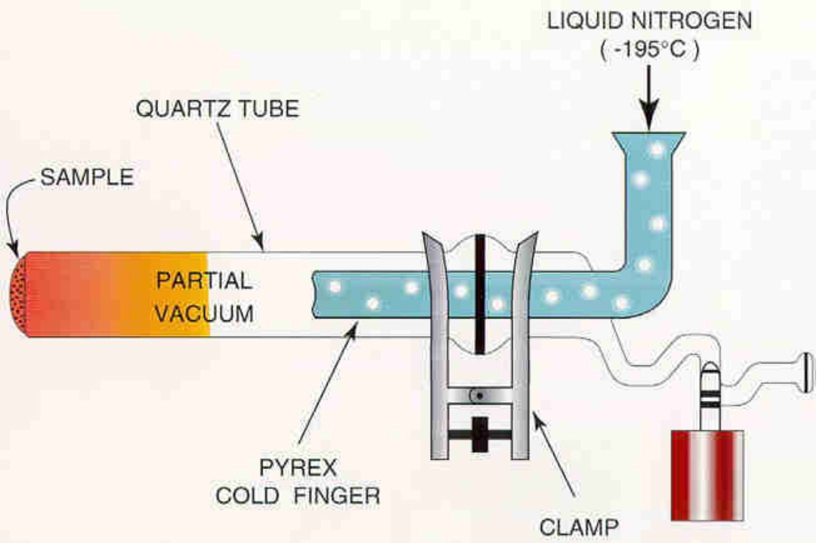


Figure 2 – A simplified version of the MOD on Vikings

FUTURE PROSPECTS

It is unlikely that human beings would stop reaching new realms of space in the vast universe. As we would like to confirm whether we are the only living beings in the universe and that there might be some form of 'parallel' world out there, it isn't likely for us to give up testing for life on another planet. Where human beings cannot reach the surface, rovers will have the responsibility of perform such complex tasks. In the future, the MODs or planetary organic detectors (POD) on board will become more and more accurate and maybe we would be able to find new forms of life in our universe.

INTEGRATING IT INTO OUR SYSTEM

This would be a specific task and therefore a POD would be carried by a small rover which is in charge of performing the specific task of life detection. Samples would be collected from the surface of the planet, either by means of drilling or digging. This would then be analysed by the POD, the data would then be sent to the mother ship whether it would have an autonomous job of analysing the data. If the data shows some interesting results, the data would be sent back to Earth for further analyses by scientists.

NAVIGATION

As rovers will usually be sent to explore far away planets, real time control of the rovers by handlers from Earth is not possible. This is due to the time it takes for information to travel from the rover to Earth and back. There is usually a time delay of several minutes. It is therefore important for the rover to be autonomous. Being autonomous means that the rover must be able to navigate safely in an unknown environment and also it must be capable of collecting and processing data. Here is an outline of the tasks a rover will be expected to perform on its own.

- Collect data from its surroundings using sensors and onboard instruments.
- Process these data, map out the terrain and work out its location.
- Plan out a route to get to assigned check points and perform required experiments.

We shall explain the navigation of the rover under two broad categories, sensors and navigation software.

SENSORS

There are many sensors built into the current rovers being used on Mars. Some of the sensors like stereo vision sensor, sun angle sensor, inertial sensor, angular rate sensor and wheel motion sensor are used mostly to aid navigation, while sensors like those used to keep monitor the rover's temperature are not particularly useful for navigation.

MOTION OF A ROVER

The rover only has to execute instructions given by scientists on Earth, although this seems like a simple task, given the time delay between Earth and a planet like Mars it becomes impossible for the rover to be controlled in real time by technicians in the control centre. We shall give a simple illustration to show how difficult navigation can be when a time delay is involved.

- While standing in a room, scan the area, plan out a route to lead to another room.
- Close your eyes and wait for about twenty minutes.
- Now try and walk to the other room using the route you planned earlier while still keeping your eyes shut.

The above example shows what the rover has to do to get itself between locations. It has to scan the area using cameras and sensors, plan a route to the new location it wants to go to and then finally make its way to the new area while trying to avoid obstacles and potential hazards. Due to the limited processing power the rover possesses, it cannot fully analyse all the information it receives via its sensors and cameras. The rover needs to know what direction it is facing and this is not always easy to establish. Also, determining the distance travelled by the rover which is integral to its route planning requires a lot more than just knowing the number of times the wheel has rotated. This is because the rover could be travelling on rocky or sandy soil and as such wheel spinning could occur, or due to the terrain the rover could have more tyre-grip on one side than the other hence giving an inaccurate measure of how far the rover has travelled. There are ways to resolve these problems, below we outline how this problems could be overcome.

SUN ANGLE SENSOR

Small orientation errors could lead to large position errors, it is therefore imperative to develop sensors that can provide absolute heading angle of the rover without recourse to the orientation of the rover. During the day, the rover can estimate its position wheel motion sensors, inertial sensors and angular rate sensors. At the end of the day, the rover will use the sun angle sensor to work out its absolute position and orientation. The use of the Sun to work out position and heading is an art that has been around since time immemorial and satellites in orbit also use the Sun to determine their altitudes. It involves using some sort of a pole and marking the position the shadow of the pole falls on a dial (or plate) at a certain time of the day. If this process is repeated for a wide range of time during the day, we can calibrate our sun dial and use this information to also work out our position since we know what direction the sun rises and what direction it sets.

Using a sun dial to find out the position of the Sun and knowing the time of day the rover can work out its heading and position. On a rover, a sun angle sensor is used instead of a sun dial. The sun angle sensor consists of a charge coupled device (CCD) monochrome camera, a wide angle lens and two neutral-density filters. The camera captures the position of the sun using the filters and thus the centre of the Sun can be calculated. From these data, the heading of the rover can be determined to an accuracy of ± 3° %.

The rovers currently in service use this method to work out their position at the end of the day to plan their route for the next day and also to determine the positioning of their communication antenna to upload data back to Earth. The next aspect of navigation we have to consider is how the rover observes its environment to avoid hazards.

STEREO VISION

Using cameras and software like GESTALT[4], the rover can be made to 'see', thus affording it the opportunity to examine the environment and figure out a safe route which it can ply to enable it to get to where it wants to go. Going back to our earlier illustration where we tried to walk to another room after closing our eyes for twenty minutes. If we now try to repeat the experiment but this time opening our eyes after every two steps, we find that it is much easier to make it to the other room without stumbling on an obstacle. The two rovers on Mars have a total of nine onboard cameras. The cameras are used for different purposes hence have different configurations. Below is a list if the different cameras onboard a rover.

- Four hazard avoidance cameras (Hazcams)

[4] GESTALT is a navigation software package used by the rovers on Mars.

- Two navigation cameras (Navcams)
- Two science panoramic cameras (Pancams)
- One science microscopic imager.

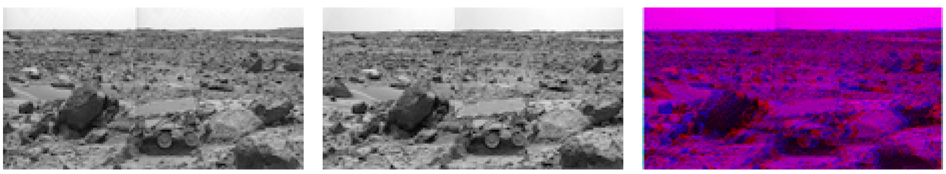
We shall go into details about the different types of cameras listed above.

HAZARD DETECTION CAMERAS

Rovers are usually deplored to distant planets and asteroids and these locations could be tens of millions of miles away from the base station on Earth. Given the constraint that data cannot travel faster than the speed of light, instructions from Earth could take several minutes to get to the rover and the rover will therefore need to be autonomous at times. To achieve this autonomy, artificial intelligence could be used in consort with images of the rover’s environment to enable safe operation. There is a need for pictures of both the front and rear of the rover to be taken, this is important because the rover can be made to move forwards or backwards without making a complete revolution. Two dimensional (2D) pictures will not be of great use here, because the depth of the scene will not be captured in 2D and this could lead to miscalculations that could result in the rover crashing into a rock or any other hazard.

Three dimensional (3D) pictures will therefore be required, and we make this possible by taking stereo pictures from a pair of cameras. Taking stereo pictures involve taking 2D pictures of the same image from two cameras that have been aligned to mimic the way human eyes capture images. The cameras provide a black-and-white 120 degrees view of the terrain. They are separated by a distance determined by the closest image they will capture. The cameras are angled inwards so that the intersection of imaginary rays projected from both cameras gives the depth that will act as a projection plane. Objects that appear before this plane will appear to be closer to the viewer and objects behind the plane appear to be further from the viewer. Using a number of techniques, the two images can then be viewed and the result is a 3D picture.

One way of viewing the pictures, will be to turn the two 2D pictures into an Anaglyph. An anaglyph is created by simply turning each 2D picture into a different colour and then superimposing both pictures. Viewing the resulting picture with corresponding colour of lens on each eye allows the viewer to see a 3D image. The figure below shows an example of how an anaglyph is combines two images to form a 3D image.



Left view Right view Anaglyph

Figure 3 – The left and the right views from NAVCAM combined to give a 3D image.

NAVIGATIONAL CAMERAS

Navigational cameras are pair of cameras that compliment the hazard cameras by providing a different view of the terrain. Like the hazard cameras they provide two black-and-white 2D stereo pictures that can be modified and viewed as a 3D picture. Unlike the hazard cameras, the navigational cameras provide a 90 degrees view of the landscape. The navigational cameras are primarily used by controllers on the Earth to map out the regions they want the rover to explore.

SCIENCE CAMERAS

Since the primary goal of any rover is to observe an unexplored region, there will be need for the rover to take pictures that will aid scientists' drive to understand a new planet or other heavenly bodies. A stereo pair of coloured cameras is used as the science cameras. Each camera has a 16 degrees field of view, which combine together to give a view that is like that of the human eye. A number of filters are employed to allow for multi-spectral imaging which mimic the view human geologist will have if they were on the planet themselves. Use of solar filters allows the science cameras to be used as a navigational aid. The cameras could be pointed at the sun with the solar filters in place and then knowing the time of day, the heading of the rover could be determined.

MICROSCOPIC IMAGER

Geological survey of the topography is integrated into the mission of any exploratory rover. Scientists often need to view rock and soil samples at very high magnifications to aid them in their studies. A specially made camera whose magnification factor can be varied is mounted on the arm of the rover and used as a microscope. Stereo images are quite possible by taking a picture, moving the camera a little and then taking another picture of the same image or view. These 2D pictures can then be converted to 3D by using the method described above or by any other method.

VEHICLE KINEMATICS AND POSITION ESTIMATION

Vehicle kinematics is studied in order to compute the wheel rotation needed to achieve the desired movement and the steering angle of the rover. The computation for a rover is very complex because it is travelling on a deformable terrain. Due to these varying conditions, the wheel sinkage is being studied. Algorithms and models are developed to understand and predict the wheel motion. Data are collected from each wheel and joint of the rover, they are then processed to compute the require motion of the wheel to effect in real movement. Further this is used to work out the motion of the centre of the rover. These computations result in accurate control over the rover motion.

Although the rover can find out its exact position and heading using the sun sensors, a fast estimation of these information are important. Currently these involve using inertial sensors as well as wheel motion.

Inertial sensors are chosen because of its properties, for example it can keep accurate track on rapid moving object, giving a good estimation of heading. This is done by integrating the data from angular rate sensors.

IMPROVEMENTS ON NAVIGATION

There are few navigation technologies that are being developed by researchers which when fully operational will aid navigation a lot. Projects like the GPS Self-calibrating Pseudolite Arrays by Stanford University Aerospace Robotics Laboratory (ARL), and Landmark-based and Star tracking navigation Systems by Carnegie Mellon University, are two such developing technologies that could make the navigation of a rover easier. One way of making an accurate and efficient navigation system, is to set up a full GPS system around the planet where the rovers would be deployed. Although this would lead to high accuracy, the one draw back is that such a system will be too expensive to setup and maintain.

An alternative will be to use pseudolites (pseudo- satellites), which use small ground-based GPS transmitters instead of satellites which is required by an ordinary GPS system. The only problem with this method is that for the system to be precise, the position of the pseudolites has to be known down to the nearest centimetre. This is not easy to establish when you are setting up the system on a different planet. Hence ARL has come up with a solution to solve the problem; they are developing a self-calibrating pseudolite array which eliminates the problem (SCPA). The idea of SCPA is to create an array of a few pseudolites and receivers which use GPS signals to determine their own location relative to other arrays, thus the rover can travel within the grid created by the pseudolites with a level of accuracy down to centimetres. Figure 5 below illustrates how this system will work.

There is another method called the Leapfrogging Multi Rover Navigation currently being perfected by ARL. The whole idea is to have four rovers mounted with transceivers working together in a group to provide navigational aid to each other. One rover moves and its relative position can be determined by the other three stationary rovers. A complete cycle of this movement is shown in figure 4. The tests conducted using this form of movement gave a drifting error of about 0.5% for the 40m the rovers were made to travel. A video clip of the real experiment can be seen on the ARL website.[5] This method results in more mobility and flexibility of the rover, however the algorithm is quite complex and more than one rover is required to implement this form of navigation. Although the test was carried out with four rovers, using three rovers still gives a high degree of accuracy, as the whole system requires at least two stationary rovers.

[5] http://arl.stanford.edu/~rover/videos/leapfrog_ames.mpg

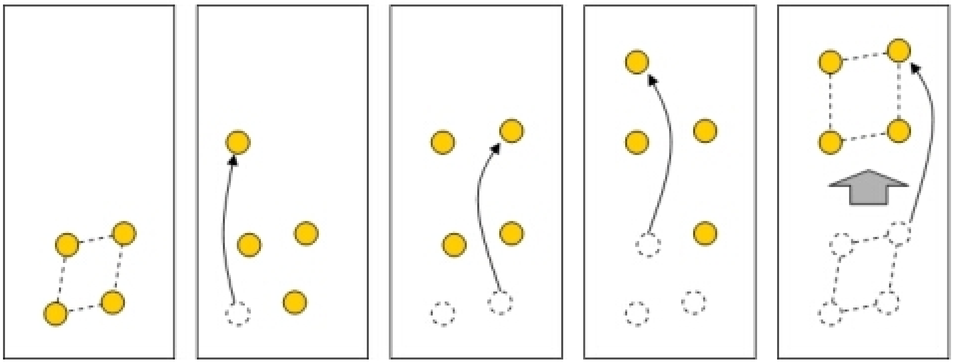


Figure 4 – An illustration of the leapfrogging method of movement, showing how a team of rovers use each others' location as a reference point for navigation.

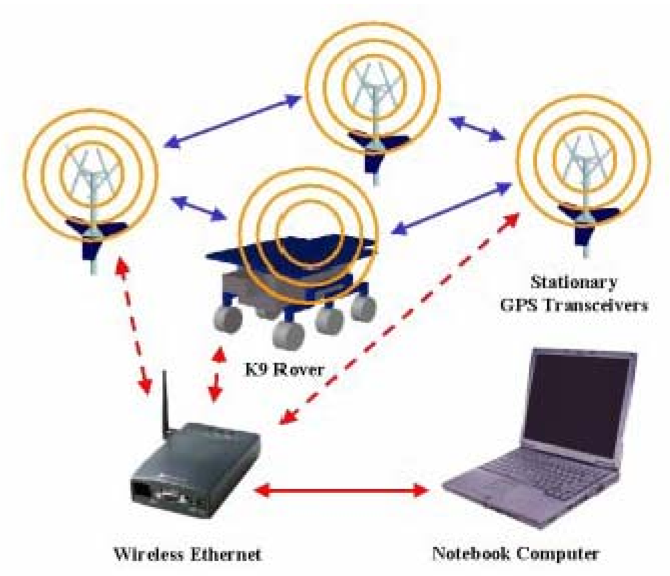


Figure 5 –SCPA architecture - A localised GPS system

POWER

Power is one of the crucial areas in any rover. If a rover has no power, it will not be able to carry out its functions and may never be able to operate again. There are so many factors that have to be taken into consideration when designing the power system. The rover has to have a low mass to allow it to be able to navigate with ease, the power system should not require frequent maintenance and also the fuel used should be long lasting or renewable. For the current rovers on Mars, their source of energy comes from the Sun. In the system we are proposing, the mother ship will generate power from both sunlight and nuclear materials. Using nuclear power will ensure that there is sufficient power even if there is bad weather and the rover cannot collect enough solar energy. The sub rovers will have batteries and will use the mother ship to charge them up. Solar panels can also be fitted on the sub rovers to supplement the power they receive from their batteries. We shall now examine the operation of solar panels and also look at the feasibility of using nuclear power.

SOLAR POWER AND SOLAR CELLS

The sun provides a constant source of energy during the day and being a renewable source systems based on solar energy are environmentally friendly. Photovoltaic power generation is reliable, involves no moving parts and is easy to operate and maintain. Photovoltaic systems are modular and can quickly be installed, and do not involve transmission lines. There are several critical factors which have to be considered when designing a solar system. A few of these factors are listed below.

- The intensity of sunlight received in the area where the rovers will operate.
- Indirect sunlight
- The temperature of the environment
- The amount of dust that is likely to be carried by winds
- Atmospheric pressure

THE INTENSITY OF SUNLIGHT

The spectrum of light received on a planet from the Sun differs from planet to planet. For example on Mars, the solar spectrum received is deficient of blue and rich in red and infrared compared to the light spectrum observed outside its atmosphere. Thus, for Mars any solar system being designed has to be built with materials that respond mostly to the red and infrared end of the light spectrum.

INDIRECT SUNLIGHT

Since the atmosphere of any planet scatters light, the sunlight hitting the solar panel comes from a range of angles rather than a straight line from the Sun. During a relatively clear day, the indirect component is relatively low, for example for a clear Martian day30% of the sunlight is indirect for an optical depth of 0.4. However, when the optical depth is high 99% of the sunlight reaching the surface is indirect.

The implication of this is that for solar cell selection, concentration technologies (i.e. using mirrors or lenses) will be much less effective than planar technologies which accept light from a wide range of angles. The efficiency of concentration technologies is also really low when the air contains a lot of dust and physical spectrum splitting devices like prisms will probably not be able to work in this environment. It is also worth noting that the indirect component of light reaching a solar panel is spectrally shifted towards the red end of the spectrum.

TEMPERATURE OF THE ENVIROMENT

The standard range of temperatures in which solar cells work effectively is between 50 ºC and 100 ºC, and thus low coefficients of temperature degradation for the solar cells are usually selected. However, on other planets the climate is usually much cooler than on Earth, hence a high temperature coefficient is desirable since this leads to higher efficiency. This factor shifts the solar cell technology towards materials that have a lower band-gap than silicon.

DEPOSITED DUST

The dust on Mars deposits out of the atmosphere and onto any flat surface; the time scale for this settling has been measured to be on the order of 100 days. On the solar arrays, a measurement on the Pathfinder mission indicated dust coverage rate of 0.3% power loss per day. This atmospheric dust will have several effects on the use of photovoltaic power systems on the surface, including decreasing the amount of sunlight on the surface and shifting the spectrum of the available sunlight, so some techniques must be developed to periodically remove the dust. Dust is expected to adhere to the array by Van der Waals adhesive forces. These forces are quite strong at the dust particle sizes. If the array surface is insulating, it is possible that we may also find electrostatic static cling, which is extremely strong. Dust-removal methods must overcome this force.

A technique combined electrostatic and Mechanical removal can remove those dusts. The array could be charged by putting incorporating a transparent conductor on the surface, and temporarily charging the array with a high-voltage supply, the dusts will be repelled from the array. And then rotate the arrays into a vertical orientation for dust to fall. This could be done with the motors used to deploy the arrays.

SOLAR CELLS

Solar cells are the building blocks for a photovoltaic system. They are made from semiconductors similar to those used in diodes and integrated circuits. The semiconductors in the solar cell convert solar energy directly into electricity by exploiting the photovoltaic effect. During the conversion, the incident light rays create mobile charged particles in the silicon semiconductor, which are then separated by the device structure produce electrical energy. The figure below illustrates the conversion process.

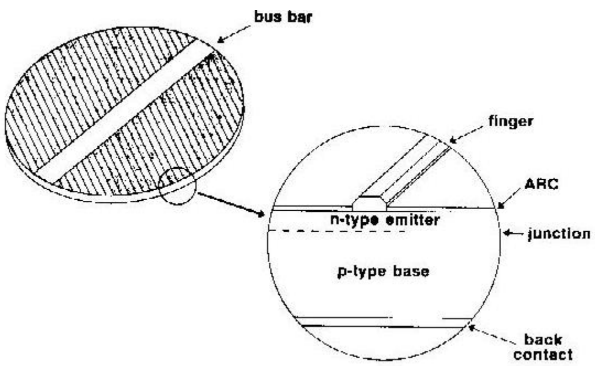
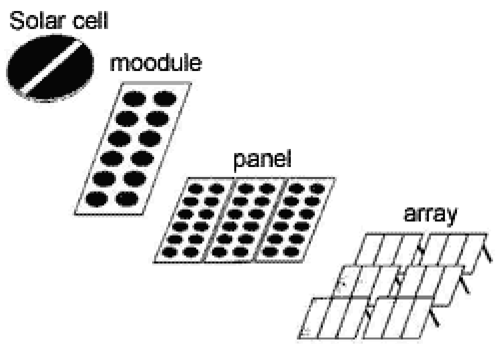


Figure 6 – A cross section of a solar cell showing its parts.

Earlier, we outlined a few factors which have to be considered during the design if a solar system, we shall now discuss a few of them in more details.

THE PHOTOVOLTIC GENERATOR

The heart of this solar power system is the photovoltaic generator. Fig 7. It consists of photovoltaic modules which are interconnected to form a DC power-producing unit. Then physical assembly of the modular with supports becomes array. Fig 8.



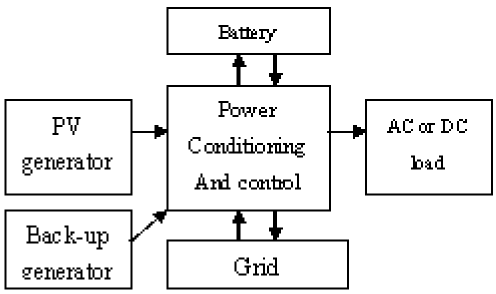


Figure 7: The photovoltaic system

Figure 8: The photovoltaic hierarchy

The cells in a module are interconnected in series. The reason comes from the electrical characteristics of an individual solar cell, a 4 inch diameter crystalline silicon solar cell, will provide between 1 and 1.5 watts under standard conditions, depending on the cell efficiency. This power is usually supplied at a voltage 0.5 to 0.6 V. Since there are very few appliances that work at this voltage, the immediate solution is to connect the solar cells in series.

A schematic diagram of a PV generator consisting of several modules is shown in Fig 9. In addition to photovoltaic modules, the generator contains by-pass and blocking diodes; these diodes protect the modules and prevent the generator acting as a load in the dark.

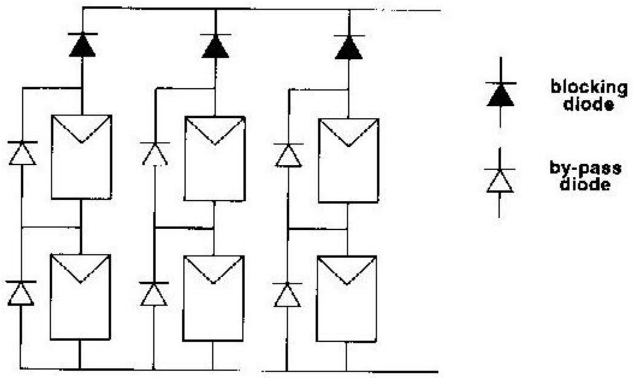


Figure 9: The photovoltaic generator

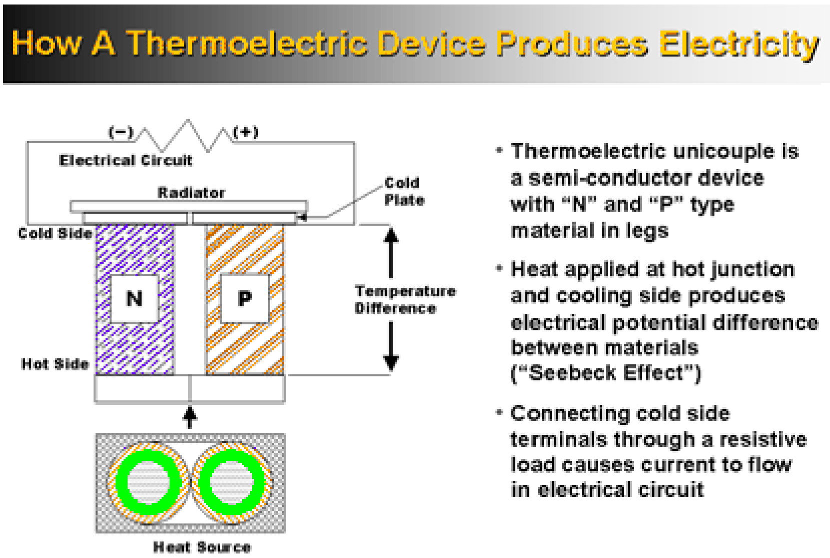
NUCLEAR POWER

As missions into space become more complex and last longer, there is a need to look at alternative ways of powering our planetary rovers. Nuclear power is one such alternative and has already been used to power a space craft. In 1997, NASA sent the Galileo probe to Jupiter, but considering the distance of Jupiter from the Sun and the amount of power needed to power the probe, scientists decided to use nuclear power to run the probe. The probe used a special self contained power source called a Radioisotope Thermoelectric Generator (RTG). This power source can be integrated in to our mother ship and provide all the rovers with a constant source of energy.

RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG)

The RTG can provide enough power for years, therefore substantially increasing the life span of any mission to space. RTGs have been used for years in missions which involve distant areas from the sun, and so far it has proven to be safe, efficient and reliable. It can produce either heat or electricity under conditions that may not be too favourable for solar cells to operate in. The amount of energy generated by RTGs has increased from a few watts to tens of watts in the last few years, and going by the rate of technological advancements hundreds of watts could be generated in the near future. The central operating principle of an RTG is the Seebeck Effect. The Seebeck effect occurs when two dissimilar materials are joined at a junction to form a thermocouple and then the other two free ends are subjected to different temperatures. The temperature difference causes diffusion of electrons across the junction (i.e. current flow) thus producing a voltage. The heat used to heat one of the junctions is provided by the natural decay of radioisotopes, thus a large and continuous source of heat is available. Plutonium is the preferred nuclear material used in an RTG. The diagram below depicts the main processes that occur in an RTG.

Figure 10- The schematic diagram of a RTG.



ADVANTAGES AND DISADVANTAGES OF NUCLEAR POWER

People generally become uncomfortable anytime nuclear power is mentioned, but it should be noted that the nuclear processes that occur in industrial nuclear reactors used to generate electricity for towns are different from those that occur in an RTG. In industrial nuclear reactors, atoms are made to release neutrons which are then used to break down other atoms, thus creating an exponential increase in nuclear fission. This whole process of nuclear fission could lead to a melt down if not controlled effectively. But in an RTG, nuclear materials are decayed in a way that does not create a chain reaction thus making the whole setup safer and making the radioisotope last much longer.

Although the RTG reduces the risk of nuclear melt down, there is still a possibility of environmental contamination if the holding vessel has a leak or crack. To reduce the risk of contamination, the nuclear fuel is stored in modular units which have heat shielding. The units are then surrounded by iridium metal and graphite blocks, corrosion and heat resistant. The plutonium used in the RTG is stored in ceramic form to reduce the risk of vaporization or aerosolization.

MATERIALS

The material used to design the rover is of great importance. If we use inappropriate materials, the rover could become damaged and this could permanently stall its mission. The various parts of the rover have to be considered separately, because each part carries out a different task and therefore is affected by different factors.

BODY OF THE ROVER

The body of the rover is called the warm electronics box (WEB). The outer body of the rover is strong and protects its computers, electronics and computers. Given the diverse weather conditions the rover could face, the body of the rover is made to operate in temperatures of ± 40 °C. On planets like Mars, the temperature at night could reach -96°C, so the rover is equipped with heaters to help keep its parts heated properly. Also when temperatures rise the radiators fitted on the rover expel excess heat to keep the rover within the range of working temperatures. A special layer of insulation called aerogel is also applied to the outer walls of the rover. Aerogel is a unique silicon based substance referred to as 'solid smoke' because it is made of 99.8% air Aerogel is one thousand times less than glass, therefore it is extra light and thus does not increase the weight of the rover substantially.

MOBILITY OF THE ROVER

The rover needs to move between locations, and as such it needs to have a structure that will support its movements. The wheels of the rover will bear the entire weight of the rover so we need them to be strong enough to carry the weight but at the same time we need them to be as light as possible to enable them to be carried in a spacecraft. Here, we will base our comparison using Mars as a reference. There is no ozone layer in the Martian atmosphere, which leads to a large temperature difference between the day and night. We have to design wheels that can withstand both extremes of temperature. The two rovers on Mars have wheels made of aerospace aluminium, but here we will offer an alternative that we think can increase efficiency of rover operations. Using a hybrid of Kevlar and carbon fibres, we can produce a material of high stiffness and tensile strength. The resulting material is incredibly strong and at the same time fantastically light in weight. The combination of Kevlar and carbon fibres also helps to dampen planetary seismic vibration.

CONCLUSION

Space exploration has come a long way from Galileo and will continue to go into unimaginable realms. The recent development of Mars rovers is only a stepping stone to what human beings can achieve. In this report we discussed some of the current technology involved in planetary exploration as well as exploring some of the future technologies to come.

Communication infrastructure is crucial to the building of a planetary rover. This is because information has to be shared in order for it to function. In the future model of the rover system, planetary rovers will need to communicate between themselves locally and also the controllers on Earth. The backbone network between the rover and Earth will be using Ka-band which is in the RF range of 18 GHz to 31 GHz. This will enable a much faster rate of data tranfer compared with the current X-band technology used in Mars-Earth backbone network. The sharing of information between rovers can be made possible by a proximity network. This Data transmission can be made possible by using UHF and will require much less energy. We also recommend that we develop a sort of interplanetary internet which can accommodate data sharing between rovers, orbiters and other planets. The orbiters will act as relays between the sub-network of rovers and other planets. With all the hardware in place and using an appropriate protocol, data can be transmitted over a long distance, overcoming noise interference.

The rovers themselves have to be autonomous as they cannot have real time communication with Earth. Therefore, in order to prevent possible damage and failure of the mission, the rover must be able to avoid any potential dangers. This is currently done by using the cameras on board. Stereo-vision is proposed as a way to give the rovers a real judgement of distance. It combines two 2D images to form a 3D anaglyph. The hazard cameras can provide a 120 degrees view of the terrain for hazard detection. Apart from hazard detection, cameras are also used for navigating the site. These cameras provide a 90 degrees view and can be used by controllers on earth to map out the regions for the rover to explore. The rover will then use the data from the camera and the sensors, such as inertial sensors to compute the necessary routes to take in order to get from one place to another efficiently. We also proposed a leapfrogging method which involves four rovers working as a team, as form of navigation. This could be performed by using a localised GPS system known as GPS self-calibrating pseudolite array instead of a globalize network of satellites.

However, even with all the navigational capability, the rovers without real-time instruction, will inevitably encounter some hazards. These hazards can be classified into external and internal failures. It is essential that the rover identifies these failures and recover from it by some mechanical or electrical response. The rover uses a MIR system which consists of the MI and MR components. The MI system will identify the faults in the rover whilst the MR will reconfigure the rover in order to instruct a recovery action to regain the safety of the rover. This system along with the navigational ability will form an autonomous vehicle which can perform complex tasks such as chemical testing. This in turn can be used to determine the existence of any biological life form.

Power consumption of the rover determines the lifespan of the rover. We mainly compared two types of power sources for the rovers, solar power and nuclear power. Solar panels currently employed on rovers can be limited by a several factors. For example, the panel only operates during daytime in the presence of sunlight. Furthermore, since the solar array works best in the presence of red and inferred spectrum, the spectrum of sunlight may be different in another planet and could possibly affect its operation. Finally, the problem of dust accumulating on the surface of the solar panel can cause a major setback on the lifespan of the rover. This can be overcome by using electrostatic forces to repel the dust and rotating the solar panel.. Nuclear power can be used as an alternative to solar arrays. The RTG uses the Seeback effect to generate a diffusion current from two different materials when they are heated by the heat caused by the decomposition of radio-isotopes. Using the RTG, the lifespan of the rover may significantly increase.

Finally, we must consider the material of the rover. The body of the rover must be able to withstand the environment of the planet in which it operates in. This means that the material must be strong. The body of the rover, also known as the WEB, contains the vital electronics and must be kept warm. A layer of aerogel and a heater in the WEB is placed on the outer layer to keep the rover at a constant working temperature. Finally, the wheels will have to be made to withstand the changing weather conditions on Mars. We propose to use a hybrid of Kevlar and carbon fibre as the resulting material is light in weight as well as possesses properties such as high stiffness and tensile strength.

The role of planetary rovers will definitely not be replaced. Just as for other rovers, these robots are assisting human beings to assess uncharted regions where human beings cannot access. The functions of these rovers would change as new technologies are developed. We hope that this report has given you an insight of the possibilities the future holds for planetary rovers.

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