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A ROBOTIC TRIAD FOR MARS SURFACE & SUB-SURFACE EXPLORATION

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1. Introduction

The Martian environment is a challenging one – the average surface temperature is –23°C and an ambient pressure of 6-7 mbar (subject to 25% seasonal variations). The US Viking lander (1976) discovered that there were no signs of organic material on the surface to ppb sensitivities due to its highly oxidised surface resultant from solar ultraviolet flux. Its surface is dominated by oxidised ferrous and ferric minerals. This year, both Europe and the US will be launching robotic missions to Mars. The European Mars Express will carry a small lander, Beagle2, to Mars with the specific task of performing a number of astrobiologically-relevant scientific studies in the restricted locale of the landing site [Sims et al 1999, 2000]. The two US Mars Exploration Rovers (MER) will provide a geochemistry-oriented study of a more extended region of the surface. Both missions illustrate the central importance of robotics to planetary exploration – Beagle2 adopts a small robotic arm and ground-penetrating mole as the main actuation devices, while the MER missions will be adopting large rovers to provide a high surface range coverage. Given that these missions are imminent, it is timely to consider potential successor missions to Mars. Given the astrobiology focus of Beagle2, it is appropriate to consider a European Mars mission with a similar emphasis. The European Aurora programme is conceived to lead through a series of robotic missions to a human mission to Mars at around 2030 despite the considerable problem of human frailty [Nicogossian et al 1994]. The role for robotics during both the robotic and human phases of the programme will be centre stage. We propose a robotic successor to Beagle2 to build on its astrobiology focus – Vanguard [Ellery et al 2003a]. The most important constraint for Vanguard is that it must fit within the Mars Express bus payload capability. The existence of the Mars Express bus design for Beagle2 adopted for Vanguard minimises the costs for the Vanguard mission. The Mars Express bus has a total payload capacity of 176 kg including orbiter instrumentation.

2. Vanguard Mission Architecture

The Mars surface package is to be delivered by a Mars Express-type spacecraft to Mars. The entry, descent and landing system (EDLS) is conceived to be similar to that employed by Beagle2 – namely, ablation shield, parachute and airbags. This aspect of the mission is currently being investigated by Kingston University and Surrey Satellite Technology Ltd (SSTL). We have selected for the purposes of design and development the Gusev palaeolake crater as the primary target for the landing site.

Our main concern here is with the surface package itself.

The scientific rationale with its emphasis on astrobiological investigation of Mars for Vanguard is described in [Ellery 2002b, 2003b]. There a number of high priority goals – determination of the geochemistry of the Martian environment, the search for sub-surface water, and the detection of biomolecular evidence of former biota. In addition, there are a number of subsidiary scientific requirements including meteorological and seismic investigation. This scientific rationale imposes two major robotic requirements:

(i) the need for multiple sample data sets from different surface locations – this implies the need for surface mobility;

(ii) the need for sub-surface data sample sets from below the oxidising conditions on the surface – this implies the need for sub-surface penetration.

Despite these requirements for actuation which imposes a complexity overhead to the mission, strong emphasis is placed on design for reliability. The approach taken to these requirements is a distributed system – a robotic triad of base-station lander (34 kg), micro-rover (26 kg) and set of ground penetrating moles (1.6 kg each). The emphasis is on exploring the sub-surface Martian environment which has not to date been explored yet which is expected to yield highly valuable data. The depth to which we wish to investigate is 5m below the estimated 2-3m depth of the oxidising layer [Zent 1998, Kolb et al 2002]. We have adopted the specification of providing three drilled holes for data-set replicability as a single drill profile would be near-useless, though five would have been preferable [Clifford et al 2001]. The surface micro-rover provides the means for deploying drillers at three separate surface sites.

For the primary scientific package, we adopt a series of advanced remote sensing instruments which offer a powerful and diverse means of investigation. By virtue of this, the primary package may be mounted onto the micro-rover connected to the sensor heads on the driller by a tether which supplies both data (optical link) and power. A laser-based confocal imager/Raman spectrometer offers the means for detecting organic material within sub-surface sediments and for chemical images of the borehole environment [Dickensheets et al 2000] – Raman spectroscopy is the current instrument of choice for terrestrial palaeobiology [Schopf 2002]. An infrared spectrometer offers the means to detect water signatures and the mineralogy within the sub-surface borehole profile. A laser plasma spectrometer offers the means for geochemical analysis of the sediment, replacing the current geochemical standard alpha-proton-X-ray spectrometer adopted on Sojournor and the MERs [Bertrand et al 2002]. All three instruments may be integrated into a single package. The use of such remote sensing instruments eliminate the need for extracting physical samples from the borehole, and indeed, the need for retraction of the drillers. Three independent drillers are deployed at three separate surface sites on a one-way trajectory. This eliminates much of the robotic complexity imposed by driller extraction. This instrument package will be supported by a ground-penetrating radar used for drill site selection [Lentz & Braun 2000]. Lander mounts the static sensor suite , namely, the meteorology pack and seismometer.

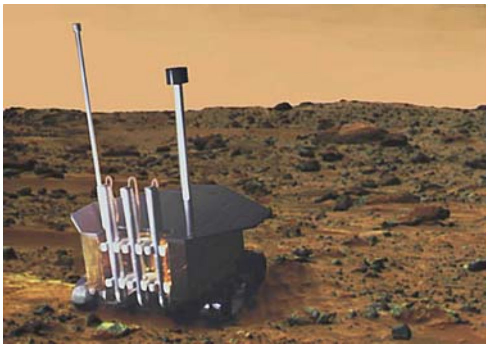

Fig 1. The Vanguard micro-rover with three vertically-mounted moles

Details of the design of the surface segment including the design budgets is given in [Ellery et al 2002c] – the total mass of the landed segment is 65.5 kg plus 60 kg for EDLS giving a total planetary probe mass of 126 kg (leaving 50 kg for orbiter instruments). We briefly consider three robotic aspects of the Vanguard proposal.

3. Vanguard Micro-rover Locomotion System

Terrestrial mobile robotics research has generally neglected the issue of traversal of rugged, natural terrains with a few exceptions. Most effort has been focussed on onboard autonomy through the planning of vehicle trajectories. The limitations in time-of-flight signalling and limited line-of-sight communication windows place a premium on autonomous navigation and robust locomotion. We are currently investigating the use of potential fields within a schema-based behaviour control approach for the autonomous navigation system [Khatib 1985, Brooks 1986, Arkin 1987].

However, the locomotion system itself defines the actuation capabilities of the robotic vehicle and the trajectories open to it – restriction of this capability limits the options open for the onboard planner or teleoperator. This in turn has a direct impact on the robotic vehicle's autonomy and performance. Sojournor had considerable difficulties in negotiating the "rock garden" due to the high density of rock distribution. Surface traverse methods for traverse of planetary surfaces are generally classed as wheeled, tracked, legged or hybrid approaches. Generally, terrestrial experiments in robotic locomotion systems have been more adventurous than those analysed for planetary application – legged systems and hybrid approaches (eg. wheeleg) have been explored. However, planetary exploration imposes a strong requirement for robust locomotion – planetary surfaces are hostile and rugged. Although legged vehicles would offer great advantages in locomotion by virtue of its requirement for only discrete footfalls, we suggest that difficulties in their control preclude them from near-term planetary exploration. Flight-tested robotic rovers for planetary deployment have to date all been wheeled vehicles – the Soviet Lunakhods 1 and 2 which were deployed on the Moon in the early 1970s, and the US Mars Pathfinder micro-rover, Sojournor which was deployed on Mars in 1997. Imminently, the US will be sending their large Mars Exploration Rovers (MER) to Mars for deployment in early 2004. All current and near-term US rover designs are based around the rocker-bogie suspension system which was demonstrated on Sojournor. The Russians by contrast have developed the Marsokhod chassis, which although a wheeled chassis system, adopts drum-like wheels. The Europeans have had an active programme of nano-rover development which has culminated in the Nanokhod rover which is by contrast a tracked system. These concepts have a number of flaws which limit their locomotion performance over rugged terrains such as those found on Mars [Ellery & Patel 2003]. We contend that there is a suitably robust yet controllable method of locomotion – the Elastic Loop Mobility System (ELMS) [Costes & Trautwein 1973, Costes et al 1973, Costes 1998]. This system is a hybrid method that combines the performance advantages of tracked locomotion with the low power requirement of wheels. We are proposing to update this concept by utilising Nitinol (49/51) for the single elastic loop utilising its elastic memory in its austeintic phase. Our studies suggest that ELMS is a promising mode of rover vehicle locomotion offering the performance of tracked vehicles by distributing load over a arge footprint but without most of their disadvantages – there are no bogie/sprocket wheels nor are their track links, substantially reducing the parts count and power consumption. It offers greater performance than the six-wheeled rocker-bogie system with only slightly higher power consumption.

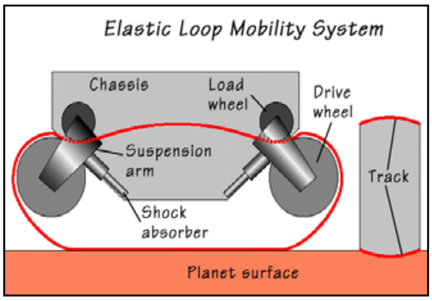

Fig 2. Elastic loop mobility system

4. Vanguard Sub-Surface Penetration

There is little doubt that sub-surface penetration in planetary explorations is becoming more important as a capability. The Rosetta lander sample drilling and distribution system (DS2) is designed to drill and acquire a number of samples from within a comet nucleus to a depth of 0.25m limited by the length of its single drill pipe [Di Pippo 1997]. The 3.1 kg DS2 comprises a tool box containing the rotary drill and sampler within a composite structure, a carousel of micro-containers, and a control unit to drive the system motors. The drill head includes a force/torque sensor to provide closed loop control and reactive capability. The DS2 requires only 5W of power. A variant of DS2, Deedri (deep driller) has been developed for a generic scientific package IPSE (Italian Package for Scientific Instruments) capable of drilling to 0.5m depth. An alternative mode of penetration through ice is adopted by the Mars Scout proposal Mars Cryoscout which proposes to descend through the Martian polar cap. Similarly, Europa's hypothetical sub-surface ocean beneath its icy crust beckons. Tethered cryobots, ice-melting penetrating robots, have been proposed for field testing at Lake Vostock, Antarctica – a 1 m long prototype of 12 cm width has been constructed which heats water at the front of the vehicle and uses gravity for downward propulsion allowing ice to refreeze behind the vehicle.

For non-polar locations on Mars however, more robust techniques are required to penetrate into the regolith. There are a number of sub-surface penetration technologies that may be deployed – these range from exotic techniques such as laser/electron beam drilling with high power requirements to more traditional methods as used in the petroleum industry such as rotary drilling. The two methods that are deemed suitable for planetary deployment are rotary drilling and percussion drilling [Ellery et al 2002d]. Rotary drilling has the advantage of a substantial body of experience in the petroleum industry but does require the automated assembly of drill segments into a growing drill-string to achieve any significant depth below 1m. The Finnish Deep Driller is a prototype mounted within the payload cab of a large nanokhod – a mobile drilling platform comprising two parallel track bodies connected by a lifting bridge and sandwiching a rotatable payload cab housing the drill and sampling system - capable of drilling to depths ~1-2m [Suomela et al 2000]. The implementation of serial drill pipes to be autonomously assembled disallows the adoption of closed loop control through a force/torque sensor. The mobile drilling platform is a tracked tethered vehicle which enables the drilling and sampling system to be delivered to multiple locations and to return to a lander sample port. The rotary drill can autonomously penetrate hard or soft soils and can drill multiple holes. It incorporates two motors – a rotary motor and a thrust motor to eliminate reliance on the local gravity field. It can recover core samples within its coring section which retain the morphology of the sediment without contamination from the surface. The requirement for autonomous assembly of drill strings is considered to be cause for concern with regard to reliability as a single-point failure mode. Although rotary drilling is ideal for core sample retrieval, the integration of in-situ sensors and sensor heads presemts a difficult problem.

Percussion drilling is considered the method of choice. Furthermore, it may be incorporated within a self-contained mole eliminating the need to autonomously construct drill strings. This is the approach adopted through PLUTO (Planetary Underground TOol) to be deployed by Beagle2 [Richter et al 2000]. The Beagle2 mole is a self-contained percussive device of length 0.325m and diameter 0.02m within a mass of 0.4 kg. A sliding hammer within the mole casing is actuated to compress a spring. Release of the sprung mass impacts the front of the casing generating a large forward force causing soil displacement. A heavy compressor mass compresses a weak brake spring with a braking force below the friction of the casing with the surrounding soil. A second shock from the internal hammer falling to its initial position causes additional forward motion. The energy delivered by both shocks are ~0.1 Nm generating a forward movement of a few mm. Each shock cycle occurs every 6s with a power input of ~3-5W, though this may be increased with a concomitant increase in power consumption. Hence, penetration to depths of ~m requires several hours. The limitation in depth of penetration of ~5-10m is imposed by the increase of resistive soil forces due to soil compaction with depth. The Beagle2 version provides the capability for acquiring ~100 mg soil samples with a small sampling valve at the front tip of the mole. By virtue of its back-hammering capability, it can be retrieved by tensioning and re-spooling of its tether. This is the mode of sub-surface penetration selected for Vanguard, though there is no requirement for retrieval of the mole to the surface. In-situ sensor heads may be accommodated within the mole. Such a device can penetrate to a nominal depth of 5m. By employing three such devices, there is no requirement to extract the moles – they can to place the sensor heads of the rover-mounted instruments into the borehole. This significantly reduces the robotic complexity that would be incurred by extracting the moles. The micro-rover can deploy each mole in turn to provide a triplicate depth profile. This requires the use of remote sensing instrumentation to eliminate the need for taking soil samples – the prime instruments will be the Raman spectrometer, the infrared spectrometer and the laser plasma spectrometer, all of which may be integrated within a single optical chain. Augmentation with thermal probes and/or magnetometers provide valuable in-situ geophysical data. The use of a ground-penetrating radar for drill site selection would ensure that submerged boulder obstacles within the regolith could be avoided but small inclusions such as clay or cemented sand (as found in deserts of the Middle East) would not be detectable. However, given that the Martian regolith will be comparatively loose in comparison with soils on atmosphereless bodies, the percussive mole offers a capable mode of depth penetration.

5. Vanguard As An In-Situ Resource Utilisation Technology Demonstrator

We submit that this approach to a post-Beagle2 robotic Mars mission represents a robust mission with high scientific returns and provides the basis for initial in-situ resource utilisation investigation for the mapping and extraction of water deposits [Ellery et al 2002e]. The relevance of Vanguard technology demonstration to technologies required to support human missions is outlined in [Ellery & Cockell 2002]. The Mars reference mission and variants thereof are generally based on a 500 day surface mission for 4-8 astronauts. A human being requires a daily input of 3.9 kg of water for consumption plus 2.3 kg of water for sanitation, less 1.8 kg of water which may be recovered through recycling (total 4.4 kg), 0.9 kg of oxygen to breathe, and 0.7 kg of dehydrated food. Water is the most critical resource and oxygen can be recovered from the electrolysis of water. Hence, utilisation of local water resources represents a considerable asset to a human Mars mission. Furthermore, the human mission will require significant mobility capabilities imposing a need for propellant (such as methane/carbon dioxide) for rovers and aircraft internal combustion engines – the Martian atmosphere of 95% CO_2 represents a bountiful resource. Bipropellant methane/oxygen with a specific impulse of 350-375s will be required for the Mars Ascent Vehicle (MAV), and perhaps, sub-orbital hoppers. Methane and oxygen can be produced through the Sabatier reaction with a Ni catalyst at 400°C: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ and $2H_2O \rightarrow 2H_2 + O_2$ (water electrolysis). More efficient electrolysers are composed of layers of solid electrolyte impregnated plastic separated by metal meshes. Ruthenium-on-alumina catalyst offers superior performance below 300^{o}C and does not produce toxic nickel carbonyl products evolved with Ni catalysts. Prior to the Mars Odyssey mission, it had been assumed that the initial hydrogen feedstock (which is recycled) would have to be transported from Earth under cryogenic storage. Furthermore, the Sabatier reaction yields a stoichimetric ratio of 1:2 for methane to oxygen while a ratio of 1:3 is required for maximum fuel efficiency. The only other alternative to the Sabatier reaction is direct reduction of CO_2 at 1100^{o}C which is energetically expensive – indeed, a further 500^{o}C increase in temperature to 1600^{o}C would enable closed cycle carbothermic reduction of metal silicate minerals for metal and silicon extraction: $Fe_2SiO_4 + 4CH_4 \rightarrow 4CO + 8H_2 + Fe + Si$. However, given that water ice may reside as close as ~1m from the surface, such resources solve many problems in the support of a human mission – water, hydrogen and oxygen (by water electrolysis) become readily available. The Sabatier reactor itself is a mature technology, though there are problems to be solved regarding the need for regenerative dust filters, reliable atmospheric pumping and atmospheric gas compression.

The chief difficulty will be in the robotic acquisition of these water resources from the sub-surfaces. This will require sub-surface penetration and the acquisition of the water ice. The aluminium silicate mineral zeolite is a porous ceramic which can absorb water or carbon dioxide. Zeolite crystals comprise alternating arrays of SiO_2 and Al_2O_3 of which there are some 50 different types Their variable ratio of silicate to alumina and impregnation of impurities generates variations in crystalline geometry characterised by a 3D network of interconnected tubes and cages which can store molecules at low temperature and release the molecules at higher temperature to act as selective molecular sponges, sieves and storage tanks. They are most commonly used as catalysts for a wide range of chemical processes. In fact, the use of zeolites has been suggested for the storage of hydrogen feedstock from Earth without the need for cryogenic cooling. Zeolite will absorb up to 40% of its own weight of CO_2 during the cold Martian night but release it during the warmer day. Zirconium oxide (zirconia) may be employed as an electrolytic cell which can split CO into CO_2 and O_2 which may be used as propellant: $CO_2 \rightarrow CO + (1/2)O_2$. This also opens up the possibility of using CO and O_2 as input to the Sabatier reactor: $4CO + 12H_2 \rightarrow 4CH_4 + 4H_2O$ (methane recycled) and $4H_2O \rightarrow 4H_2 + 2O_2$. Zeolite will also absorb water [Williams et al 1995] - the zeolite of choice is UOP Molecular Sieve 3A which has an aperture size of 3A slightly larger than a water molecule thereby excluding carbon dioxide, nitrogen and argon contaminants from the Martian atmosphere. The zeolite may be mounted as a cap to the rear of each mole. As the mole descends, the zeolite cap is left sealing the top of the borehole. As the mole descends, it exposes any water ice deposits to ambient Martian atmospheric pressure causing them to sublime. The zeolite caps absorb the released water vapour. Cross-correlating the infrared spectrometer's water signature with the absorbed water vapour captured by the zeolite cap would provide a measure of efficiency of water mining. A critical issue would be the lateral thickness into the borehole walls of the sublimed water ice. If indeed that liquid water does exist in the sub-surface at such shallow depths (though this is not expected above depths of ~100m), hydrostatic pressure would provide the means to mine water efficiently with a wide catchment area around the borehole. Regeneration of the zeolite would require heating to 130^o C to release 5% zeolite mass of the adsorbed vapour leaving a residual fraction ~20% of the zeolite mass of water vapour – this could be achieved in conjunction with the Sabatier reaction though would not be required as part of the Vanguard mission which is concerned demonstrating the water mining principle.

6. Conclusions

It is our contention that Vanguard offers a low-cost, highly capable Mars exploration mission with a number of demonstrable robotic capabilities – surface traverse, sub-surface drilling and in-situ resource utilisation through water mining. From a scientific viewpoint, it would provide the first physical depth profile of the Martian sub-surface (pressure, temperature, friction, magnetisation), the first survey of the sub-surface through ground-penetrating radar and seismic survey, the first demonstration of sub-surface drilling to depths below the oxidising layer to 5m depth, the first mineralogical study of Martian sediment, the first geochemical analysis of Martian regolith at depths below 1m, the first astrobiological investigation of the sub-surface below 1m, and the first technology demonstration of sub-surface water mining in support of a human Mars mission. More generally, Vanguard offers technology demonstration of a number of essential robotic componernts required for a human Mars mission – robotic rovers to demonstrate traverse of ~ km over rugged terrain and robotic drilling for sub-surface exploration and mapping. We believe that Vanguard makes an ideal choice as an Aurora Arrow mission.

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