Nanorover Technology and the M USES-CN Mission

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ABSTRACT

The National Aeronautics and Space Administration has been sponsoring efforts to develop very small planetary rovers for Mars and other planetary bodies. Recent advances in microtechnology and mobile robotics have made it feasible to create extremely small automated or remote-controlled vehicles which open new application frontiers. One of these possible application is the use of nanorovers (robotic vehicles with masses <<1 kg) in planetary exploration. The MU SES-CN mission is a proposed mission which has baselined the nanorover as a payload. MUSES-C is a Japanese sample return mission to the near-earth asteroid Nereus. MUSES-CN is a NASA payload planned for inclusion in MUSES-C which will be up to 1 kg of mass delivered by the MUSES-C spacecraft to the asteroid surface. (NASA was offered this payload by the Japanese space agency lSAS in return for support with deep space communication, navigation, and sample aerocapture.) The rover planned for MUSES-CN is adapted directly from the vehicle developed under the NASA Nanorover Technology program. The mission concept for MUSES-CN is for the rover to be jettisoned from the MUSES-C spacecraft during the first of three sampling descents to the surface of Nereus. The rover would then explore Nereus during the subsequent two to four weeks while the MUSES-C spacecraft remains in the vicinity of Nereus. The MUSES-C spacecraft will function during that time as the communications relay between the rover and Earth. The rover will move around the surface of Nereus, taking images and IR spectra of a variety of locations.

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Planetary science missions have been under increasing pressure to reduce their launch mass requirements so that less expensive launch vehicles can be used. For example, the Delta launch vehicle is less than one-fifth the cost of the Titan, and the Taurus is less than half the cost of the Delta, in order to launch on these inexpensive vehicles, significant reductions in mass must be achieved. For example, the science package on post-Pathfinder landers is expected to be 20 kg or less. To achieve those aspects of scientific exploration requiring mobility, any rover component of the science payload must compete effectively in terms of mass against other payload options. Microrovers (-1 0kg) were conceived partly in response to this [1], and soon after nanorovers (10s or 100s of grams) were proposed for the same reasons **[2].** The NASA Nanorover Technology task has been established to create a vehicle which would enable some mobility-based science surveys, such as mineralogic classification, and the search for water ice or other volatiles on Mars or comets at or very near the surface with a small, perhaps negligible, fraction of the science payload for envisioned for upcoming missions. This latter point makes it conceivable that nanorovers could fly as a secondary payload on most landers using whatever mass margin is left over at launch time. Alternatively, they could be the prime payload of microlanders for Mars, small bodies, or the moons of the gas giant planets.

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The vehicle developed thus-far in the Nanorover Technology task is considered as the prime candidate for NASA participation in the Japanese MUSES-C mission which will return a sample from the asteroid Nereus, launching in early 2002. The chairman of the NASA Small Body Science Working Group (as well as of the MUSES-C Science Working Group), Joe Veverka, has stated that "the value of [NASA/ISAS] cooperation would be increased dramatically by the inclusion of a NASA-provide, scientifically instrumented microrover". He further states that the science goals of the [1 kg Max.] rover will be to make "texture, composition and morphology measurements of the surface layer at scales smaller than 1 cm, investigations of lateral heterogeneity at such small scales, investigation of vertical regolith structure by taking advantage of disturbances of the surface layer by microrover operations, and to measure constraints on the mechanical and thermal properties of the surface layer"[3].

One of the most scientifically interesting locations on Nereus for the rover to examine in detail is one or more of the actual sampling sites of the MUSES-C spacecraft. The MUSES-C spacecraft will take samples by impacting the surface of Nereus with a projectile of about 10 grams with a velocity of about 300 m/s. This projectile will presumably cause a cratering event which will result in ejects being thrown off the surface. This ejects will be captured and will become the sample to be returned. One possible role for the rover to play is to make a detailed inspection of the sampling crater. Of particular interest is any possible layering of the terrain, especially if it might be lost or confounded by the ejection or capture processes. Other functions which the rover will perform include assessing the diversity of the asteroid surface and the whether the sample sites are representative of the surface as a whole, and also to give microscopic images of the full variety of surface features.

CURRENT PLANETARY ROVERS

The current state-of-the-art in planetary surface rovers is probably exemplified by the Pathfinder microrover, which launched in December 1996 for arrival at Mars in July 1997. This rover, named Sojourner, has a mass of 11.5 kg and a size of about 65x45 cm with six 13 cm diameter wheels. Pathfinder was launched on a Delta 11 7925 expendable launch vehicle, which is one of the larger launch vehicles planned for use in the planetary exploration program, with a cost of some $60M. Clearly the cost of a technology development activity could be recouped entirely if it were to save a significant fraction of the cost of a single launch vehicle.

sCIENCE INSTRUMENTS

The first activity conducted by the Nanorover Technology task was to establish a credible science instrument suite. Alternative instruments of many sorts were considered; a multi-band visual imager with near-IR point spectrometer has been selected. This combination was judged to bc the lowest mass, highest science return instrument complement which can be integrated at acceptable cost, which works in Earth test environments, and which minimizes safety hazards such as radioisotopes or ionizing radiation. Using the Active Pixel Sensor 256x256 imaging array developed in the JPL MicroDevices Laboratory (MDL), the camera with filter wheel will give images in a number of spectral bands in the visible out to about 1 micron with resolutions as high as 10 microns per pixel. By covering the wavelength range of 1-2.5 microns, the near-l R spectrometer will give mineralogic data on a huge variety of possible minerals including important clays and carbonates. Stimulated by the MUSES-C activity, an Alpha-Proton X-ray Spectrometer (APXS), miniaturized from the one being flown on the Sojourner rover, is being actively considered as a third instrument. This science complement would give essentially complete and unambiguous mineralogic and morphologic information about the target sites visited.

VEHICLE CONFIGURATION

A second activity under this task has been to develop a high-mobility vehicle configuration which can meet the mission and science requirements. The selected design is shown in Figure 1. This "posable strut" concept is for a self-righting and/or upside-down-operable articulated vehicle chassis. It includes the ability to recover from overturning as well as body pose control for camera/instrument pointing, sampling, or other functions. It accomplishes this with a remarkably simple, top/bottom and right/left symmetric mechanism which has a small number of moving parts and very low mass. Operation in extremely low gravity (e.g. on the surface of an asteroid) can be accomplished since no free pivots are used (which would have too much friction to articulate freely in a microgravity environment). No prior vehicles are known which combine many or most of the desirable features achieved in this design:

- can operate upside down
- can intentionally flip over and recover from accidental overturning
- can place the body flat on the ground (e.g. for sensor placement)
- can lift individual wheels and set them on top of obstacles (instead of pushing the wheel against the obstacle and requiring enough traction to lift the wheel against gravity)
- are actuated only by one gearmotor for each wheel (no additional motors are needed to actuate the additional degrees of freedom)
- allows torque from the gearmotor driving one wheel to assist another wheel when extra torque is needed
- can articulate to keep all wheels providing optimum traction even in arbitrarily low gravity fields
- can "hop" and reorient the body during ballistic hops in very small gravity fields.

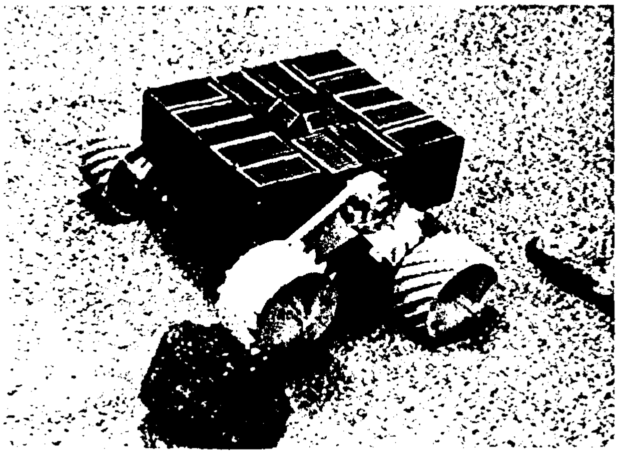

Figure 1 - Nanorover with posable struts

Mobility in a microgravity environment presents a number of challenges which can be overcome with this vehicle configuration. These include the tendency of the vehicle to overturn easily (the kinetic energy is greater than the gravitational potential energy of tipover in the expected Nereus gravity field of 20 μg at a speed of less than 1 cn~/see) and the need to point or place instruments against the surface of the asteroid, since there may not be any "rocks", as such. (The surface properties of the asteroid are more or less completely unknown and may range from bare rock to dust to a fractal distribution of rock fragments.) Movement of the struts will allow "hopping" out of severe terrain or just for relatively rapid, long range mobility.

The main chassis of the vehicle is composed of two printed circuit boards, which on the inside face have all the electronic components mounted, and on the outside have the solar cells, radio antennas, proximity sensors, etc. The kevlar circuit boards planned for the flight version are very strong, light, and have low thermal expansion, and so make good structural members. These circuit boards are used as the "optical bench" of the camera and spectrometer, thereby making maximally efficient use of available mass. This is a special case of what has become known as the "sciencecraft" development philosophy: perform maximal cross-utilization of all components to maximize science return while achieving necessary engineering functions.

One particularly good example of this maximal cross-utilization is the focus mechanism of the camera. interviews with planetary scientists confirmed that a sequence of images is needed to establish scientific context when a science target such as a rock is approached. Each image should have a scale no more than 2-5 times smaller than the previous image. At the finest scale, the images must give a resolution of better than 10 microns per pixel if most crystal boundaries are to be seen and cleavage angles measured. These constraints can be shown to require that there must be a mechanical focus mechanism which can be positioned accurate to about 1 part in 1000 over a lens stroke of about 3 cm.

The existence of this focusing mechanism has profound consequences for the configuration of the spectrometer. Conventional wisdom in the flight community is to use detector arrays to avoid the mechanical scanning which historically was used to multiplex a point detector over a span of wavelength or a spatial dimension. However, because we already plan to have a precision scanning mechanism for camera focusing, we can use it also to scan an inexpensive point detector over the infrared spectrum. This also increases the performance, because 1000 element IR detector arrays (the effective number needed to equal the performance of the mechanical scan mechanism) do not yet exist (and even the 256 or 512 detectors are too expensive for this task).

The commercial market recognizes that mechanical scanning of a point detector is a cost-efficient solution for IR spectrometry. One company, Analytical Spectral Devices (ASD), has a product which mechanically scans a holographic diffraction grating over a pair of Indium-Gallium-Arsenide point detectors to give 10 nanometer spectral resolution over the spectral range from 1 to 2,5 microns. This spectral range and resolution allows many likely minerals to be discriminated, including the Olivines and Pyroxenes which will reveal the initial igneous composition of the planet, as well as the iron oxides, oxyhdroxides, carbonates, clays, and sulfates which are sensitive indicators of the alteration environment since formation. We are working with ASD and their suppliers to integrate identical optical and detector components as used in their design for this application. This product is described at: "http://www.asdi.com/asd/prod/fs_fr.html".

Having derived an attractive science payload and mechanical configuration, several other engineering questions have been addressed. One is that all components considered for application to this have been explicitly examined as regards possible flight qualification for the radiation and thermal environments of Mars as well as inner solar system small bodies. Most digital and analog (but not RF) components used in the prototype have been successfully tested at -1 OOC; most are available in rad-hard versions as well or have been qualified for Sojourner. Complete analog and digital printed circuit board testing at - 10OC and below is planned for April 1997. Design of a space-qualifiable version of the RF subsystem is underway, using the same Surface Acoustic Wave (SAW) technology used in the (Figure 1) prototype but with FET-based active components instead of junction transistors, which fail at low temperatures.

Survivability of the small commercial gearmotors which have been in the first prototype has been addressed. Testing experience with the motors for the Pathfinder Rover indicate that the key areas of concern are lubrication, bearings, and brushes. We have received custom versions of the small motors used in the prototype with dry lubricant and with ball bearings. With these changes, brush life is expected to be the limiting factor. The brushes on these motors are made of precious metals, which on Pathfinder were found to have a useful life of about 30 million armature revolutions in a Mars-like atmosphere. However, in the hard vacuum of a small body mission, brush life is expected to be very short, of order 100,000 revolutions. For a mission such as MUSES-C, this would lead to a rover range (using the 1000:1 gearhcads and 6 cm wheel diameters) of only -20 meters. The next lifetime limitation is the armature bearings; at 15000 RPM or higher the 100M revolution lifetime which might be expected in hard vacuum would still come in a hundred hours of continuous operation. As a result, another research avenue which has emerged under this task is the issue of ultraminiature actuators for extremely wide temperatures and hard vacuum.

Reevaluation of the motor, gearhead, and wheel design of the nanorover from basic physical principles has suggested a somewhat non-intuitive solution: that not only the brushes but perhaps also the gearhead can be eliminated. Specifically, a mathematical model was constructed which considered the entire wheel, gears, motor, cable harness, and drive electronics as a system whose mass and complexity was to be minimized. The resulting minimum mass approach for very small rovers is a brushless, direct drive, DC motor which uses a cylindrical rotor of the most powerful available permanent magnetic material @eodynliunl-iron-Boron) attached directly to the wheel. A light nonrotating cage supports the electrical winding fairly close to the magnetic rotor. Motors of this type have been built for direct-drive robots which have very high performance, with an output torque of approximately 0.25 nt-m pcr $W^{1/2} Kg^{5/6}$ [4]. It turns out that the rim thrust of such a motor is proportional to the square-root of the mass of the motor, so if the motors are some fixed fraction of the vehicle mass and the rim thrust must equal the vehicle weight, then there is a certain vehicle scale (for a given available power and choice of materials) below which the direct-drive approach is superior to a gearhead. Even if the rover were large enough that a gearhead is required, it will have a relatively low ratio and thus not require high rotor RPMs, thereby eliminating the lifetime concern of the conventional high-speed armature. It also turns out that the rim thrust of such a motor per unit mass is inversely proportional to the density of the conductor used in the winding times the square-root of its conductivity. Since aluminum is 58% more resistive than copper but only 32°/0 as dense, a winding made from aluminum will deliver 2.5 times as much rim thrust per unit mass as a copper winding. A prototype motor using this concept is being created now, will be evaluated, and an appropriate motor incorporated into the next generation nanorover. This same approach will be used to research and develop an actuator for the internal optical system, where (surprisingly) motor life is even more of an issue than for the wheels, due to the large number of expected scans of the spectrometer and focus mechanism and the high effective gear ratio of the focus mechanism.

Long range navigation requires a different control paradigm from a lander-local scheme such as used in the current Pathfinder rover on Mars. Two things are required to allow long-range navigation: hazard detection and maintaining a stable heading reference. We plan to maintain a stable heading reference with sun sensing. As seen in Figure 1, the top surface of the rover has a small pyramid of solar cells, we can determine the approximate direction to the sun by measuring the relative output of these cells. Hazard detection will be accomplished by two means; by using IR proximity sensors and with focus-based ranging to identify hazards (and potential science targets) at some distance in front of the vehicle. In this mode of operation, the focus adjustment on the camera is set to some intermediate distance (say 25 cm). As the vehicle moves, small "windows" in the image will be processed to compute the variance of the image data over the window. When the variance peaks, the object seen in that window is presumably in focus. As mentioned above, development of behaviors which take advantage of the high mobility characteristics of the posable-strut chassis in performing hazard avoidance is a major research objective of the task. A final goal of the Nanorover Research Task is dust control. Since the rover is solar powered, accumulative dust from a Martian surface or from asteroid sample ejects could reduce rover performance if not mitigate it. Plans are to study this in FY'98.

CONCLUSIONS

A nanorover containing a panoramic/microscopic imaging camera and a near-IR spectrometer is being considered as a NASA-supplied payload, dubbed MUSES-CN, for the Japanese MUSES-C sample return mission to the asteroid Nereus. The mobility chassis uses a novel posable-strut mechanism which is able to accommodate the microgravity environment of Nereus by self-righting, hopping, and other advanced behaviors. The primary mission is to study surface inhomogeneity of the asteroid, with particular interest focussed on evaluating the sampling craters left by the sampling device on the host spacecraft. To accomplish this objective, new technology has been developed in mechanisms, actuators, electronic packaging, and software to coordinate all the various functions of the device.

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