

# **Snow White and the 700 Dwarves**

## *A Cooperating Robotic System*

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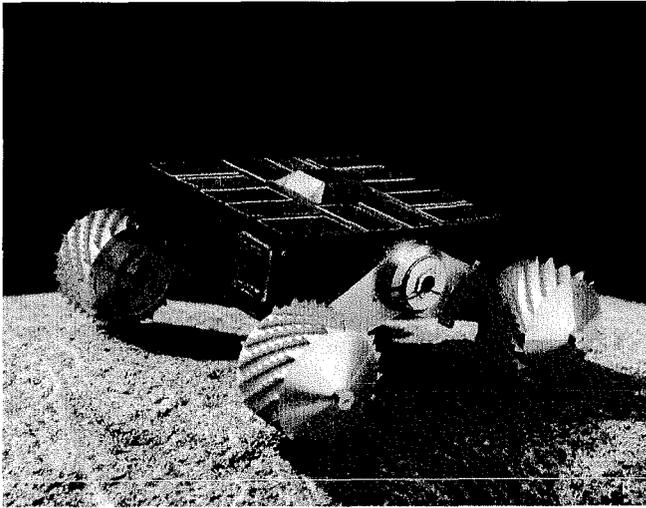
**Abstract:** Detailed scientific study of possible sites on Mars such as extinct hot springs may require robotic excavation of the sort generally associated with archaeological "digs" on Earth. This paper describes a system developed to explore the feasibility of building such a robotic network. A scaling analysis shows that, for a given landed mass, it is better to break the payload into as many small vehicles as possible, due to the surface-to-volume implications on the power-to-weight ratio for the system using solar power. Each small vehicle must be equipped with a shovel and hopper to move loose material, and a provision for a percussive hammer to break up hard soils and rocks. A central mast rising from the nearby lander supports stereo imaging and a computer providing central co-ordination of activities. Each vehicle has limited sensing (e.g. no vision) but is designed to follow simple commands (`goto(x,y)`) and rules (keep to the right of oncoming traffic). The outer surface of each vehicle is arranged to capture solar energy, and the lander mast can be configured with a foil reflector to bounce sunlight down into the excavation to keep the vehicles powered most of the day. Thus we have a system consisting of a single tall mast with a pair of stereo cameras at the top and a large, silver reflector hanging down, together with a large number of small robots, each having a pick and shovel. This system has been dubbed "Snow White and the 700 Dwarves".

**Key words:** Co-operating Robots, excavation robots

## 1. INTRODUCTION

### 1.1 Development of the Concept

Previous work from the NASA Nanorover Technology task [1] and the MUSES-CN flight project [2]) has developed the key technologies for a nanorover qualified for space flight (~1kg, Figure 1) which combines advanced mobility (4-wheels with active articulation, self-righting), advanced sensing (capacitive proximity sensing on each wheel and accurate laser ranging to 10 meters), advanced cryovac microactuators (-180C to +125C operational thermal range), and advanced chip-on-board, wide-temperature electronic packaging of a 32-bit flight computer with a custom flight gate array I/O. This foundation can be used to develop a first example of a robotic outpost system that could perform a useful function on Mars or other planetary surface.

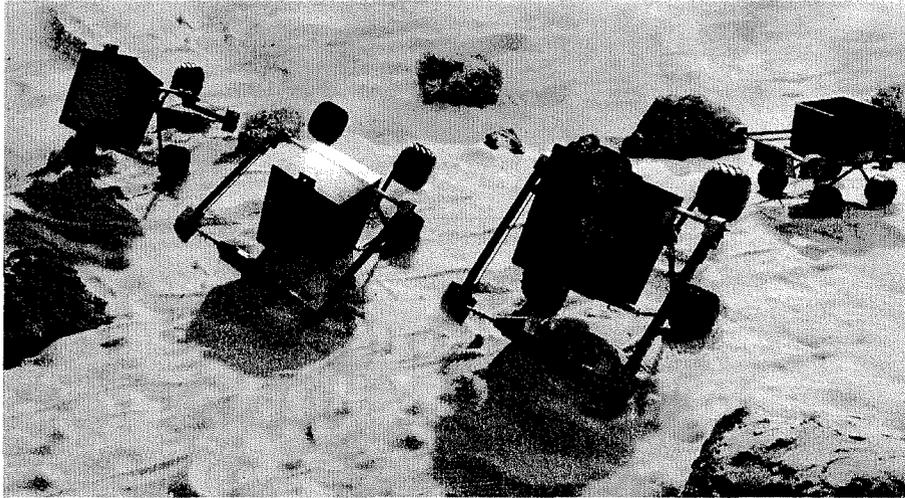


*Figure 1.* Nanorover Prototype, approximately 20 cm long overall

The mission concept for this system is to have a solar concentrator deployed from a mast on the lander. This reflector concentrates sunlight onto a small region of the ground. A group of solar powered rovers gather at this site and use percussive devices to excavate terrain material. Each has solar panels on the exterior of a "dump truck" vehicle configuration, where the excavated terrain is stored for transport. Each small rover might have a mass of approximately 1 kg, while 1000 kg or more may be landed on Mars by a single lander, so it may be possible to put hundreds of these small vehicles on Mars in a single mission. This multitude of small rovers with

percussive rock breaking devices, together with the solar concentrator tower, has been dubbed "Snow White and the 700 Dwarves".

The objective of the present activity is to explore the scaling relations and a distributed control methodology needed to achieve this objective. Specifically, there are many scaling advantages for using large numbers of small solar powered robots, most importantly the increased power to weight ratio and amortization of development costs over a large number of vehicles. In this task, four testbed vehicles have been built to perform an initial demonstration of excavating an open pit (Figure 2).



*Figure 2. Nanorover Outpost Vehicles in various phases of operation*

## 1.2 Mission Applications for Co-operating Robots

Excavation of open trenches is of profound interest to both the Planetary Science and Human Exploration and Development of Space (HEDS) communities due to its applicability in study of areas of intense science interest, such as extinct hydrothermal deposits, as well as emplacement of habitats under radiation shielding, digging utility trenches, or extraction and processing of the near-surface volatiles thought to exist at some latitudes on Mars. Excavation makes an ideal first co-operative task for a robotic outpost: it scales extremely well to small sized vehicles, it requires co-operation to be effective, and it can be done with solar power and thus eliminates the need for an elaborate means for storing and distributing energy to the multitude of vehicles. Many other proposed robot outpost applications do not exhibit any "advantage of scale" in that they merely

multiply the capabilities of a single rover proportionately, such as in parallel exploration of a site by many uncoordinated explorers. The present concept is most attractive in conjunction with a solar concentrator tower, allowing a relatively inexpensive distribution of power to the vehicles. This combination, "Snow White and the 700 Dwarves" allows many exciting missions on Mars, in the polar regions on Earth's moon, at the polar regions on Mercury, and perhaps on comets and asteroids. There is an especially exciting possibility with respect to the lunar polar regions where, because of the small angle between the moon's equator and the ecliptic plane, a tower only a few hundred meters high could intercept continuous sunlight which could be reflected 24-hours a day down into foil-lined tunnels excavated into the putative permafrost. Such a tower would be relatively easy to implement in the low gravity, disturbance-free environment of the moon.

The fleet of dwarf rovers could excavate these tunnels first for science, looking at a layered history of cometary impacts on the moon and possibly even examine history of the larger asteroidal impact events on Earth. (It is possible that the impact event thought to have caused the extinction of the dinosaurs may have lofted sufficient seawater to have left a record of volatiles and possibly even microfossils deposited in the cold traps at the lunar poles.) Moreover, these tunnels could provide vast quantities of water and perhaps other volatiles for use in life support, material processing, and propulsion for future HEDS endeavours. If the quantities of volatiles prove adequate, these lunar polar bases could well become the springboard for human settlement of the entire solar system, due to the resulting low cost to send large quantities of reaction mass and life support fluids to interplanetary or Earth orbits. These activities would in turn be enabled by the hard-working fleet of dwarf robots tirelessly toiling in the reflected light of Snow White.

### 1.3 Scaling Laws for Planetary Rovers

It is clear that the surface area, and therefore the solar power collection area, of a rover scales with the square of its dimension, assuming fixed proportions. The mass, weight in a gravity field, and resistance to motion scale with the cube of the dimension. Therefore the power to weight ratio scales inversely with the dimension, so that small rovers have relatively large power-to-weight ratios and visa versa. This power-to-weight ratio is the main determinant of the overall vehicle performance, just as with terrestrial vehicles. For example, given a fixed coefficient of rolling resistance, the maximum speed of a vehicle is linear with the power-to-weight ratio. This leads us to the somewhat counterintuitive result that, for solar powered vehicles, a small vehicle can go twice as fast (even up a hill)

as one twice as big. Or it can carry twice the load, in proportion to its size. This further leads us to the conclusion that, if we can only land a fixed mass on the surface of Mars, we would be well advised to break that mass into as many small vehicles as possible.

Of course, there is a limit to this. As a practical matter, there is overhead mass associated with the control system, the power system, and the structure which is not necessarily scale invariant. Small motors tend to be less efficient than large ones, small batteries have a greater fraction of their mass devoted to inert packaging, etc. This means that, given the current state of technology, there is an optimal size for the vehicle.

More importantly, the forces needed to excavate rock or packed soil do not scale well to small vehicles. The use of percussion breaks this adverse quasi-static scaling relationship, allowing the advantages of small robots to be applied to the task of excavation. Small vehicles have a difficult time generating sufficient forces to excavate any material, even in the smaller unit quantities accepted by the small body. Percussion offers a way out of this dilemma. With percussion, the peak forces that can be exerted by the vehicle are no longer limited to some small multiplier of the vehicle's weight (which is itself reduced in planetary environments over that on Earth). In a percussive system, this multiple is increased by the ratio of the hammer forward stroke distance to its stopping distance. For hard rock or packed regolith (planetary dust/sand or other particulates) this ratio can be very large, of order 1000 or more. This means that a hammer can momentarily impart forces of 1000 times the weight of the vehicle to this type of terrain. If the surface area of the hammer face is small, this means that pressures far in excess of the compressive strength of the terrain can be exerted, which pulverises the medium into a network of microcracks.

## 2. APPROACH

The basic principles to be explored by this task are that small, distributed, solar powered robots with percussive excavation tools can perform soil/rock excavation and manipulation tasks better than larger or quasi-static systems for a given launch mass. The approach is to create a small fleet of miniature robotic vehicles incorporating the essential features described here: a low-power "dump truck" with a hammer for breaking the terrain medium, a scoop for loading it into the hopper, and appropriate minimalist sensing and computing environment to allow an effective collective behaviour in excavating a single, coherent "dig". This small fleet is used to develop the needed software to allow a demonstration of the enormous scaling advantages of the distributed excavation approach.

## 2.1 Vehicle and System Description

The vehicles themselves are four-wheeled "rocker bogie" vehicles [3] manufactured using 3-D photolithography for the body and wheels, with machined metal parts for the running gear and scoop assemblies. The electronics consists of a commercial equivalent of the rad-hard R3000 32-bit processor developed by Synova running under the VxWorks real-time operating system on a custom printed wiring board with all the relevant robotic I/O. Each individual rover has pitch and roll sensors, motor position and current sensing, and provision for capacitive proximity sensing in each wheel. Each vehicle has a 2-DOF scoop able to swing entirely around the vehicle, enabling excavation of loose material, dumping of that material, self-righting of the vehicle from any orientation. Also, a central system "Snow White" has been built which allows co-ordination of the vehicles under command from a human operator. A custom-developed radio system allows communication between Snow White and each of the rovers on a single channel. This radio, built using a chip set from RF Monolithics, Inc., gives 9600 baud communications at ranges of about 100 meters.

The control methodology for this system is strictly hierarchical. Snow White is responsible for maintaining an estimate of the position of each vehicle, and commanding them to their next task. Co-operative excavation occurs because Snow White commands successive rovers to dig in slightly different spots that, taken together, take on the geometry of the finished excavation. Each vehicle only is responsible for dead reckoning a relatively short distance, since it has no sensors to correct for wheel slip or other navigation errors. Snow White, on the other hand, has a global sensor (the mast mounted cameras) in a fixed co-ordinate system, and so can maintain a coherent long-term representation of the state of the entire system.

The software functionality implemented to date on each vehicle includes operator-designated waypoint dead reckoning (using differential odometry for heading estimation). Scooping, dumping, self-righting, and motor stall recovery behaviours have been implemented and tested. As with Sojourner, which melded the behaviour-control approach with "waypoint designation" to allow an effective command-level interface, this system will continue to evolve that methodology with "rules of the road" (e.g. "pass to the right") [4]. A custom communication protocol has been developed which allows one or more rovers to act as intermediate relay nodes to pass messages to any rover which strays too far from Snow White.

Software that has been implemented for Snow White includes "blob tracking" of one or multiple rovers by the Snow White cameras. This algorithm relies on the fact that the only parts of the scene that move are the rovers. Each rover is tracked to ensure that it is staying on the commanded

sequence of waypoints. Other software that has been developed and tested includes provision for simultaneous teleoperation of multiple rovers, update of individual rover calibration parameters, patching of the flash memory, and rover engineering downlink telemetry interpretation, display, and logging.

### 3. CONCLUSIONS AND FUTURE WORK

The hierarchical organization of this system is a natural consequence of the nature of long-distance communications. Because such communications (e.g. between Earth and Mars) are necessarily energy intensive and require significant infrastructure, there is generally only a single asset at any site which is capable of providing such a service. With only one element of the system able to receive human commands, it is natural for that element to be the local "commander". In this case, it is the lander that delivers the rovers to the surface and out of which pops the mast for Snow White. It seems quite possible that this same "communications bottleneck" applies to many sorts of systems, such as military applications. In that event, it seems possible that this hierarchical structure would be appropriate where the commander has the long-range radio and the "foot soldiers" have only local communications. While it is true that such a hierarchical organization might be less fault tolerant than one where any element can take over any job function, in fact the uniqueness of the long range communication asset implicitly makes the system asymmetric and inhomogeneous. The advantage of such a hierarchical system is that it is clear how to develop the software to make it work.

In the next year of funding, it is expected that behaviours will be implemented incorporating the capacitive proximity sensing functions built into the existing hardware. This hardware excites each wheel as a "free space" capacitor, and can detect very small changes in the capacitance of each wheel. This allows estimation of the proximity and amount of dielectric material in proximity to the wheel. For example, if a wheel starts to go off the edge of a cliff, the capacitance will drop abruptly even before the wheel loses contact with the terrain. The capacitance will increase if the wheel is against an obstacle, or near to another vehicle. This sensor data will be used to implement behaviours including the "pass to the right" function mentioned earlier as well as cliff avoidance.

Also, the percussive mechanisms for breaking up rocks and "hard pan" soils will be added to the vehicles. The dynamics of reaction of the vehicle to both the forward stroke of the hammer and to the resulting impact have not been explored. One intriguing approach is to have a hammer on the end of a swing arm, which can also then be used as a scooping device. The

hammer can be accelerated upwards on one end of the semicircular stroke, so that the reaction force on the rover body is downwards, preventing unwanted rover motion. The hammer can then coast around the arc to either a vertical face impact or further around to hammer on the horizontal ground, or anywhere in between. Minimal reaction forces from the hammer impact will be imparted back to the rover via the relatively long, free swing arm.

In conclusion, the key figure of merit for the overall system is the mass of excavated material per unit system mass (rovers plus additional infrastructure) per unit time. The activity will be judged successful if the scaling advantages of the fleet of small rovers are realized: that the fleet of rovers are able to excavate many times their own mass per year of operation.

#### 4. ACKNOWLEDGEMENT

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#### 5. REFERENCES

- [1] Brian H. Wilcox, Annette K. Nasif, and Richard V. Welch, "A Nanorover for Mars", *Space Technology*, Vol 17, No 3-4, pp 163-172, 1997.
- [2] Brian H. Wilcox and Ross M. Jones, "The MUSES-CN Nanorover Mission and Related Technology" Proceedings IEEE International Conference on Robotics and Automation, Workshop on "Mobile Micro-Robots", Roland Siegwart, ed, paper 0-7803-584628, San Francisco, CA, April 2000
- [3] Donald Bickler, "The new family of JPL planetary vehicles", proc. *International Symposium on Planetary Mobile Vehicles*, Toulouse-Labege France, September 28-30, 1992.
- [4] Brian H. Wilcox and Tam Nguyen, Wilcox, "Sojourner on Mars and Lessons Learned for Future Planetary Rovers", Society of Automotive Engineers publication 981695, 1997.