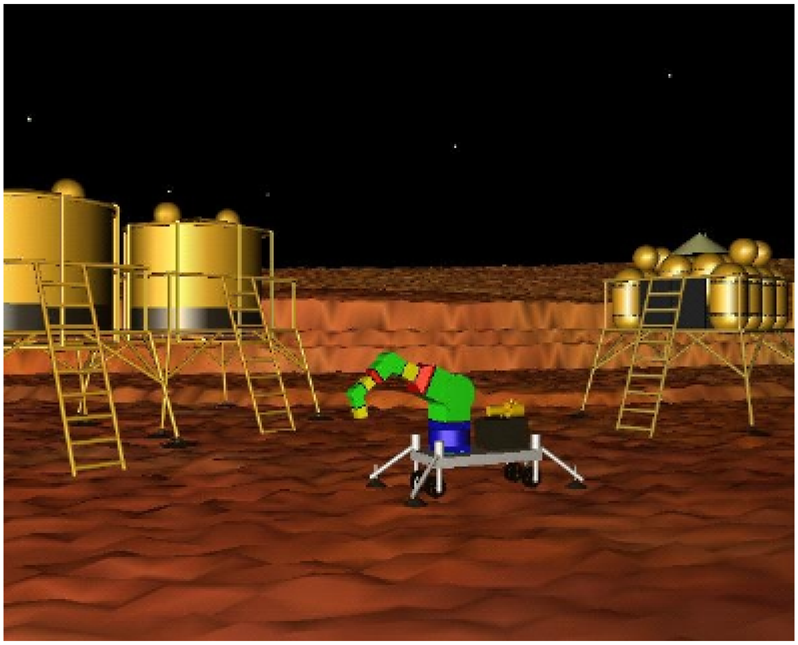
A Modular Robotic Infrastructure to Support Planetary Surface Operations



Final Report

On

Phase 1 Study

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1 Abstract

This Phase 1 project studied a Planetary Surface Modular Robotic System (PSMRS). Human exploration of the Moon and Mars is planned for the 2010-2020 timeframe. Extensive use of robots will reduce costs and increase safety. A wide variety of tasks, requiring large a variation in robot capabilities, will be performed. For example, large quantities of regolith may need to be manipulated, requiring bulldozer-like capabilities. Also, delicate scientific instruments may need to be deployed. Creating individual robots for each task is not an efficient approach, especially since not all tasks can be foreseen.

The PSMRS could facilitate many NASA missions. The phase I project studied the use of the PSMRS to support human exploration of Mars. This mission fits the 10-20 year timeframe corresponding to NIAC objectives.

Revolutionary robotic solutions may be required. The PSMRS is proposed to address these unique challenges. Here a robotic infrastructure, rather than an individual robot(s), is proposed. The system is based on a fundamentally modular design to efficiently address the unique challenges of planetary surface operations. The system consists of modules that can be assembled into dramatically different robots to perform dramatically different tasks. This approach promotes efficiency and reliability through adaptability.

The PSMRS does not require revolutionary enabling technologies. Instead, it represents a revolutionary approach to robot design compared with robots currently being developed. The approach could have an important and immediate impact on mission planning.

The Phase I study successfully demonstrated the concept's feasibility and met the objectives outlined in the Phase I proposal. Mission requirements were developed, important tasks were identified, and an inventory of modules was created. Robots were simulated using adequate mathematical models of the environment, robot, and task. The simulations demonstrate the scientific feasibility and credibility of the approach.

Nine robots were described as examples of the diversity of robots (and capabilities) that can be produced. All nine robots were constructed using only 26 modules, showing the benefits of the approach in terms of launch mass and volume. Three of the robots were simulated performing representative, mission-relevant tasks including soil manipulation, instrument deployment, and science sample collection. Animation of these simulations is included with this report.

2 Introduction

A revolutionary approach to space robotics is proposed. It involves designing a robotic system to be applied to a wide variety of tasks rather than an individual robot(s) for each task. This is accomplished through a modular approach to robot design at a very fundamental level. This concept is used to develop a robotic system to support exploration called the Planetary Surface Modular Robotic System (PSMRS).

This approach represents a fundamental change in the approach to planetary robots. Robots currently under development for near-term missions (Mars exploration and sample return missions through 2007) are relatively conventional Sojourner-like robots (Volpe *et al*, 2000; Hayati *et al* 1998; Schenker, 1997). These are fixed configuration robots that are designed to perform a few specific tasks (e.g. move and deploy a science instrument). The capabilities of these robots cannot be changed as new mission requirements arise. These robots are good solutions for the near-term objectives (0-10 years), however, a new approach to robot design will be required to meet the future long-term objectives (10-20 years) such as human exploration.

In this new approach modules are assembled to produce a robot for a specific task. The set of modules, called an inventory, includes actuated joints, links, end-effectors, sensors, and mobility units. The same inventory can be assembled in different configurations for different tasks, see Figure 1.

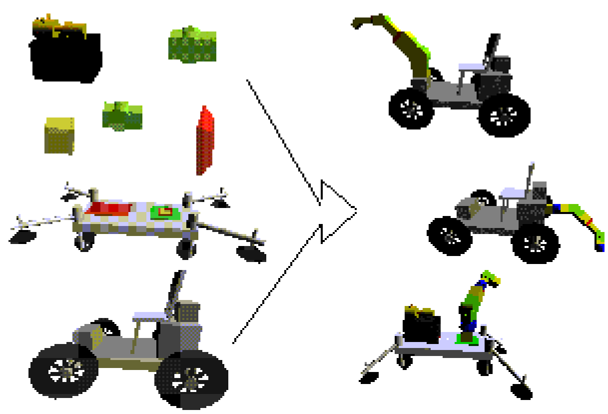


Figure 1: The Modular Robot Concept

In general, this reconfiguration will need to be done autonomously. Many solutions are possible. One solution is to have a base module with the capability of manipulating other modules. A second solution would be to have a pre-assembled modular robot dedicated to assembling other modular robots. Also, if such a system is used to support human exploration, an astronaut can perform the assembly.

This approach greatly expands the capabilities of the robotic system over traditional robot designs. It also promotes reliability because different configurations can compensate for the failure of individual modules.

It is possible that some tasks cannot be addressed with the PSMRS and will require a specific machine (or robot). This will not be known until detailed missions are developed. However, the advantage of the modular system is that a single set of modules can be reconfigured for many tasks and can be adapted to address unforeseen tasks. The PSMRS may not be able to perform all tasks, but its flexibility has advantages.

In this report the objectives of the Phase 1 study are reviewed (Section 3), the work done to accomplish these objectives is outlined (Section 4), and the results of this work are presented (Section 5). Finally, the work is summarized (Section 6) and future work is outlined (Section 7).

3 Phase 1 Objectives

The proposed concept represents a fundamentally new approach to planetary robot design. The preliminary work in this phase 1 study is aimed for the 10-20 year timeframe, corresponding with NIAC's objectives and the timeframe NASA proposes for the human exploration of the Moon and/or Mars.

The PSMRS does not require revolutionary enabling technologies. Instead, it represents a revolutionary approach to robot design compared with robots currently being developed. Since all enabling technologies are currently available, the proposed approach could have an immediate and important impact on NASA's human exploration plans.

The objective of this project was to study how the modular robot design concept can best be applied to planetary surface operations, and to significantly influence mission planners.

The results of this project demonstrate two specific advantages of the modular robot design concept:

- the ability of a modular system to accomplish a wide variety of tasks that would normally require numerous traditionally-designed robots
- the increase in system reliability – a factor of the utmost importance on a Mars mission – that is realized with an adaptable modular approach

The project will seek to influence mission planners by demonstrating the usefulness of modular robots to improve future mission scenarios. Most mission scenarios include an unmanned “cargo” mission as a precursor to a human landing. Other proposals favor the establishment of a "robot colony" where many robots will work together to extensively explore a given region. The PSMRS could be useful in both these mission paradigms.

4 Phase 1 Work

The phase 1 work began with a study of current mission scenarios. Knowledge of these mission plans will be required to identify representative tasks for robots. From the mission scenarios design specifications were developed that describe the requirements for the system. The specifications were then used to develop a modular inventory from which specific robots, for the representative tasks, could be constructed.

4.1 Mission Studies

The original focus of this study (as presented in the Phase 1 proposal) was to develop a modular robotic infrastructure to support human Mars exploration. The advantages of the modular concept are not limited to this specific mission so the focus (in Phase II) will shift to include a wider variety of missions including lunar and asteroid exploration as well as the concept of "robot colonies".

Many proposals have been developed for the further human exploration of the moon and Mars (Zubrin, *et. al*, 1991; NASA, 1989). The most notable among these reports is referred to as the Stafford Report or the Space Exploration Initiative (Stafford, 1991). This report, prepared in 1991, outlines America's plans for further exploration of the moon and human exploration of Mars. It is slightly dated, but presents many of the trade-offs and technical challenges to accomplish these exploration goals.

A more recent study, prepared by the Exploration Office and the Advanced Development Office at the Johnson Space Center , describes a *Reference Mission* for Mars exploration (NASA, 1998). This study presents the *Reference Mission* with the intent of stimulating "further thought and development of alternative approaches". This reference mission is used as the demonstration platform for the modular robotic concept described in this report. The concept is not limited to this reference mission, but this mission provides a realistic and relevant application for the concept. The mission has the first crew landing on Mars in 2010 and future crews occupying this site indefinitely. This timeframe fits exactly with the 10-20 year outlook of this Phase 1 study.

This reference mission refers to the use of robotics in the exploration of Mars. No specific goals or tasks are directly outlined for robots. However, a robotic precursor mission is described. This precursor mission is very similar to the "robot colony" concept except here there is the expectation that humans will arrive. The robotic precursor mission will have three goals:

- Exploration - gather information about Mars that will be used to determine what specific crew activities will be performed and where they will be performed.
- Demonstration - demonstrate the operation of key technologies required for the reference mission
- Operation - land, deploy, operate, and maintain a significant portion of the surface systems prior to the arrival of the crew.

Each of these goals includes significant challenges for robots and requires a wide variation in capabilities. The first goal of exploration will require a high degree of mobility. This goal will require robots to travel many ($\approx$ 100) kilometers and perform typical exploration activities such as imaging, scientific measurements, and sampling. This task is similar to the near-term missions (0-10 years) planned by NASA. However, when the exploration activities are complete it would be desirable to use the robot hardware for other purposes.

The second and third goals would require robots to deploy, operate, and maintain surface systems such as in situ resource utilization equipment, science instruments, habitats, and power generation equipment. These are all mechanical systems that will require maintenance and repair.

The reference mission also refers to robotic tasks in support of human activities. One such task is to provide mobility for astronauts on the scale of 1 to 10 kilometers. Another stated activity includes maintenance of the Mars outpost.

The reference mission is used as a demonstration tool for this project. The diversity in robot capabilities that will be required is clear. Also, it is not possible to foresee all required robot tasks, especially in areas such as maintenance and repair.

4.2 Design Specifications

The reference mission contains challenging robot tasks requiring a wide variation in capabilities. This section outlines the design specifications for the PSMRS.

There are a set of general design specifications that apply to all planetary exploration systems including tight mass and volume constraints. For obvious reasons, the total mass and total volume transported must be minimized. From this point of view the advantage of using a modular system is clear. The total mass/volume dedicated to support systems such as robots can be minimized if this mass can be adapted to many tasks (i.e. a set of modules that can perform many tasks will require less mass than a specific machine designed for each task).

Another general design specification is that the robotic system must be extremely reliable. The reference mission establishes a permanent Mars outpost with new crews arriving at the same location indefinitely. This further emphasizes the need for reliability. Part of the reliability requirement means the robots need to be easily repaired. The advantage of a modular approach is that broken modules can be easily replaced in the same manner that the modules are assembled into robots. Also, a new robot could be constructed from different modules to perform the task in a new way. The modular system also makes it easy to add new functionality (new modules) as different cargo or crew missions arrive. The incremental build-up of the Martian outpost is a cornerstone of the reference mission.

Because of the complexity of the mission, not all tasks can be foreseen. The extreme remoteness of the mission dictates that these unforeseen problems must be solved with the available elements. This further emphasizes the need to have an adaptable system.

More specific design constraints relevant to the reference mission were also developed. For instance, the reference mission calls for a long-range pressurized rover and a short-range un-pressurized rover. The pressurized system is not included in the PSMRS. The un-pressurized rover must travel up to ten kilometers. It must be capable of transporting one astronaut (168 kg) and carry 500 kg of useful payload. It must be capable of climbing slopes up to 25 degrees and travel at a nominal speed of 10 km/hour. It is probable that the rover will use an internal combustion engine as a power source (Jochim, 1999).

The reference mission includes some "heavier" manipulation tasks such as manipulating large amounts of soil. This may be needed for science excavation, in situ resource utilization, radiation protection, and/or habitat/instrument deployment. These "heavier" tasks have much different requirements in terms of precision and strength compared to "lighter" duties such as scientific instrument deployment and assembly.

4.3 Inventory Design

An inventory of modules was then developed using this information. The inventory must be capable of producing robots that address the above specifications and tasks.

The goal of inventory design is to create the smallest inventory of modules that can be assembled into the largest diversity of robots (i.e. enough robots to accomplish all required tasks).

In inventory design, the *level* of modularity is important. A *low-level* inventory would contain very basic elements such motors, gears, bearings and nuts and bolts. A *high-level* inventory would contain complex elements such as limbs or arms. A low-level inventory offers more flexibility in the robots that can be constructed, however assembly of the robots is much more complex. Conversely a high-level inventory can produce fewer robots but the assembly is simplified. The inventory designed in this study has a moderate level of modularity offering a balance between the diversity of robots and ease of assembly. Examples of the diversity of robots that can be produced are presented in Section 5.1.

The inventory created is broken into six categories corresponding to the basic elements of a robot. These categories are base modules, power supplies, actuated joints, kinematic links, end-effectors, and sensors.

4.3.1 Module interface

To build functional robots from the modules, each module must be capable of interfacing with all other module. The interface can be broken into three categories: 1) mechanical interface, 2) electrical interface, and 3) information interface.

Three standard sizes were chosen for the mechanical interface. The first two sizes are intended for general purpose, or "light" duty robots, the third size is for "heavy" duty tasks. The module interfaces are squares connecting surfaces of 10cm, 15cm and 30cm. The modules can be attached in 2 orientations as shown in Figure 2, further increasing the diversity of robot assemblies.

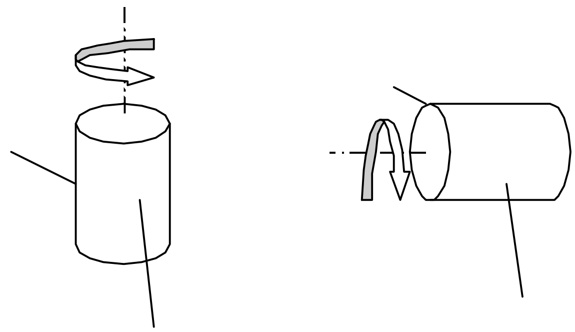


Figure 2: Module Orientation

The interface will also transmit electrical power between modules. The electrical power will be transferred using two conductors. Each module requiring electrical power will have the necessary (voltage) regulation as an integral part of the module.

Information will need to be transferred between modules; this can be done using electrical or optical connections. Information transfer can occur in many ways; one method would use serial communication such as RS435. Each module will have a processor to handle communication between modules and local control (e.g. position control of a joint).

4.3.2 Base Modules

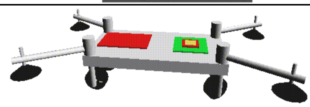
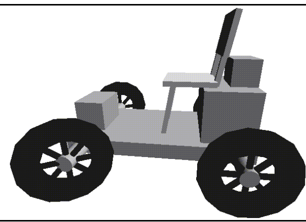
Base modules are used to support the robots. Power modules and Sensor/Control modules will be connected to one area of the base module and a serial robot will be connected to another. Every base requires a power module and a control module to operate. The power module will provide energy to the system. The control module will perform command and communication operations. Even though every robot requires power and control these functions are kept separate they can be easily tailored to the specific robot assembly and task (high/low power; long/short range communications) and can be easily repaired/replaced.

There are three base modules in the inventory including mobile bases and fixed (immobile) bases, see Table 1. The fixed base (#101) is designed for areas where a task is frequently performed. It is a very simple module that provides a platform on which robots can be constructed.

The mobile bases will expand the usefulness of the PSMRS by expanding is zone of operation. There will be two types of mobile bases, one for unmanned operation, and the other for human transport. The unmanned mobile base (#102) can be used for both short-range exploration (< 1km) and for general manipulation tasks.

The human transport base (#103) has been the topic of discussion between the PI and JSC. JSC has awarded the PI a very small research grant to study the design of such a vehicle. The human transport base is un-pressurized rover designed provide mobility for one astronaut. It can travel up to ten kilometers and carry 500 kg of useful payload. It is designed to climb slopes up to 25 degrees and travel at a nominal speed of 10 km/hour.

Table 1: Base Modules

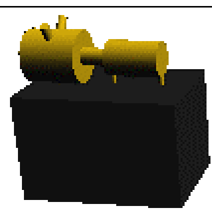
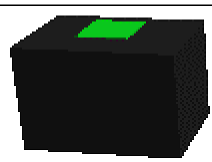
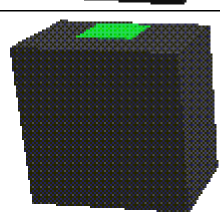
ID#		Size (cm) L x W x H	Type	Notes
101		125 x 75 x 15	Fixed Base	
102		125 x 75 x 35	Unmanned mobile base.	• Autonomous or tele-operation • Range < 1km • 75 cm outriggers
103		185 x 95 x 70	Human Transport base	• Can be autonomously, human or tele-operated • Range < 10 km

4.3.3 Power Modules

These modules supply power to the robot assemblies. Table 2 shows the three power modules included in the inventory. Two provide electrical power through batteries, the second generates electrical power using an internal combustion engine.

The reference mission describes fuel (methane) that will be extracted from in situ materials (atmosphere). This fuel may be used for the assent vehicle and for internal combustion engines to power various surface systems including the PSMRS. This module (#001) will make it possible to produce powerful robots for long-range exploration. The energy that can be produce by such an engine per unit volume is much grater than can be stored using current batter technology.

Table 2: Power Modules

ID#		Size (cm) L x W x H	Type	Notes
001		45 x 30 x 45	Internal Combustion Engine	• Energy is limited by fuel supply. • Max. Power: 3 kW
002		45 x 30 x 30	Small electrical supply	• Energy: 8 A-hr at 24V • Max. Power: 100 W
003		45 x 30 x 45	Large electrical supply	• Energy: 50 A-hr at 24V • Max. Power: 650 W

The two remaining power modules store electrical energy, a small (#002) and a large (#003) unit are included. The use chemical batteries and provide less power and less total energy then module #001, but are useful for "lighter" and short-range tasks.

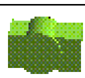
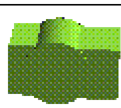
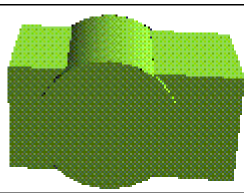
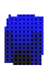
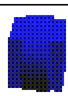
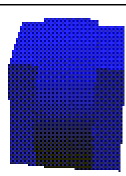
All power modules will need a method to replenish their energy. There will need to be a facility as part of the Mars outpost where all modules will be stored. This facility will also recharge/refuel the power modules. This facility is not addressed by the phase I study.

4.3.4 Actuation Modules

Actuation modules are the core of the robotic system, see Table 3. The actuation modules produce rotational motion. No translation actuators are included in this inventory, but such modules could be easily added. The rotational modules can be divided into two groups: rotary joints (#201, #202, #203) and axial joints (#204, #205, #206). The rotary joints produce rotation about an axis that is perpendicular to the body of the robot (elbow). The axial joints produce rotation about an axis that is parallel to the body of the robot.

The actuation modules can also be divided into two categories based on their size. The first category includes smaller to medium modules for general manipulation tasks (#201, #202, #204, #205). The second category includes one or two large modules for "heavy" tasks (moving regolith, lifting with a crane, etc).

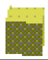
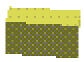
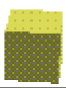
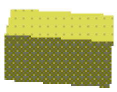
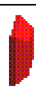
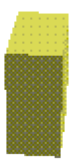
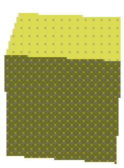
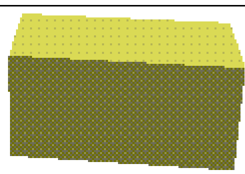
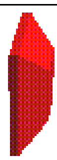
Table 3: Actuation Modules

ID#		Size (cm) H x W x L	Type	Notes
201		10x10x20	rotary joint-small	• Torque: 25 N-m
202		15x15x30	rotary joint-medium	• Torque: 100 N-m
203		30x30x60	rotary joint-large	• Torque: 2000 N-m
204		10x10x10	axial joint - small	• Torque: 25 N-m
205		15x15x15	axial joint - medium	• Torque: 100 N-m
206		30x30x30	axial joint - large	• Torque: 2000 N-m

4.3.5 Kinematic Modules

The Kinematic modules, shown in Table 4, are used to alter the configuration (or shape) of the robot. Link modules change the distance between the robot's joints. This greatly affects the capabilities of the robot in terms strength, reach, and accuracy. Adapter modules are also included to transition from 30 cm modules to 15 cm modules (#311) and from 15 m modules to 10 cm modules (#307).

Table 4: Kinematic Modules

ID#		**Size (cm) W x H x L**	**Type**
301		10 x 10 x 5	Short-10 cm interface
302		10 x 10 x 10	Medium-10 cm interface
303		10 x 10 x 20	Long-10 cm interface
304		15 x 15 x 7.5	Short-15 cm interface
305		15 x 15 x 15	Medium-15 cm interface
306		15 x 15 x 30	Long-15 cm interface
307		15 x 15 x 5	15 cm to 10 cm adaptor
308		30 x 30 x 15	Short-30 cm interface
309		30 x 30 x 30	Medium-30 cm interface
310		30 x 30 x 60	Long-30 cm interface
311		30 x 30 x 10	30 cm to 15 cm adaptor

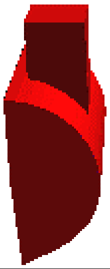
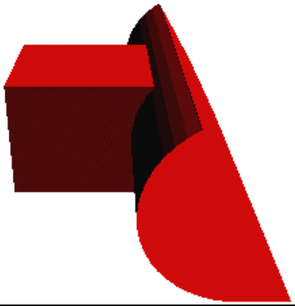
4.3.6 End-Effector Modules

The end-effector modules, shown in see Table 5, allow the robots to perform tasks. This category includes general manipulation end-effectors such as grippers (#401 & #402) to be used for tasks such as assembly and sample collecting.

End-effectors with more specialized uses are also included. A large scoop (#403), similar to the bucket on a back hoe, will allow robots to dig and level ground for both science and maintenance purposes. A plow blade (#405), similar to a snowplow, is included for similar operations. Finally, a wench (#404) is included to create robots with crane-like capabilities.

Science end-effectors could be added to the inventory to perform specific science tasks. For example, an Alpha Proton X-Ray Spectrometer (APXS), similar to the instrument used on the sojourner rover, could be added.

Table 5: End-Effector Modules

ID#		Size (cm) W x H x L	Type	Notes
401		10x10x15	Gripper - small	• General manipulation • 10 cm interface
402		15 x 15 x 22	Gripper - Large	• General manipulation • 30 cm interface
403		30 x 30 x 38	Scoop / Bucket	• digging • science • 10 cm interface
404		15 x 15 x23	Crane/wench	• environment manipulation • general surface operations • 10 cm interface
405		90 x 35 x 28	Regolith blade (snow plow)	• environment manipulation • science • radiation shielding • 30 cm interface

4.3.7 Sensor & Control Modules

The sensor and control modules were not completely developed during this six-month study. Different sensor packages will be needed depending on whether the robot will operate autonomously, be tele-operated, or be directly commanded. Sensor modules will be needed to provide information for navigation and hazard avoidance.

Two sensor modules are provided as examples. The first module is a vision sensor (#501). It contains a pair of stereo cameras that can be moved in yaw and pitch. The cameras are also on a telescoping shaft so the robot can change its point of view. The second sensor is a laser-based range finder. This sensor is representative of one of the sensors need for autonomous operation in unstructured environments.

Finally, control modules will be needed. These modules provide high-level control, communication, and mission planning. A control module will be required for every robot assembly. The detailed design of a control module is critical, but it does not alter the physical capabilities of a robot assembly. Control modules were not included in the six-month study. Previous research has developed techniques for planning and control of modular robots (Farritor, 1998).

Table 6: Sensor and Control Modules

ID#		Size (cm) L x W x H	Type	Notes
501		15 x 15 x 20-60	Vision Sensor	• Stereo vision • Telescoping up/down • Yaw and pitch actuation
502		15 x 15 x 20	Range Sensor	• Optical

4.4 Simulation

A detailed physical simulation was created to demonstrate and evaluate robots. The development of this simulation is not straightforward because it must be capable of simulating any robot configuration.

The simulation considered physical constraints such as interference, geometric limitations, static stability, actuator saturation, and power consumption. The simulation is used to insure the feasibility of the design and to demonstrate that the concept is sound.

The simulation was written from scratch using the C++ programming language. Details on the physical models used to crate the simulation are given in Appendix A.

4.5 Animation

An animation was created to visualize the results of the simulation. A videotape of the animation, showing the three representative task described in Section 5, is included as part of this report. Images from the animated tasks are also given in Section 5.

The animation was created from scratch using a Silicon Graphics computer and the OpenGL programming environment. The program is capable of animating any assembly of modules from the inventory described above.

5 Phase 1 Results

This section demonstrates the diversity of robots that can be developed from the inventory and shows how they can be applied to various mission-relevant tasks.

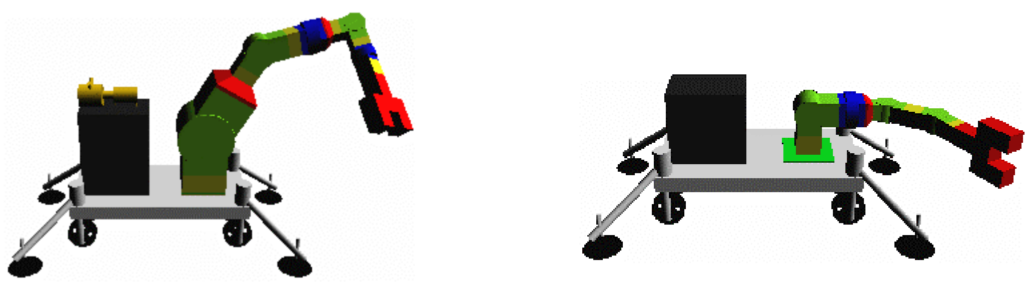
This inventory is capable of producing many (>10^8) robots (Farritor, 1998). Nine robots are described as examples of the diversity of robots and capabilities. Six robots are briefly described in this Section 5.1 and three different robots are presented performing three representative tasks in Sections 5.2, 5.3, and 5.4.

All nine robots shown in this report are produced from only 26 modules of 18 distinct types. The tasks presented in this report are meant to represent a variety of tasks that could be performed by a modular robotic infrastructure. The specific tasks were chosen to align with the needs of reference mission describe in Section 4.1. The tasks are not meant to represent how things will actually be done on a planetary mission. Instead, the tasks demonstrate the advantages of the modular infrastructure approach.

5.1 Robot Diversity

Two short-range mobile manipulation robots are shown in Figure 3 (the end-effectors are not drawn to the correct scale). Both robots use the #102 base module. This module has 4 wheels for mobility and outriggers for stability during manipulation (see animation on video tape). Robot A, Figure 3 a), has a very strong first joint (#203) and a long reach. The robot is capable of lifting 408 kg and has a reach of 2.02 meters (assumes Martian gravity, see Appendix A for further assumptions). This robot uses the internal combustion engine as a power source. Robot B is a smaller robot with a smaller first joint (#102). It can only lift 30 kg and has a reach of only 1.34 meters. However, the configuration of its distal joints allow it to manipulate objects in the horizontal plane with low power consumption.

Both these robots could be used for general manipulation tasks (deploy instruments, collect samples, perform habitat maintenance). However, Robot A would be better suited to short duration, heavy tasks (replacing an ORU), while Robot B could be used for long range, light duty tasks (collecting rock samples).

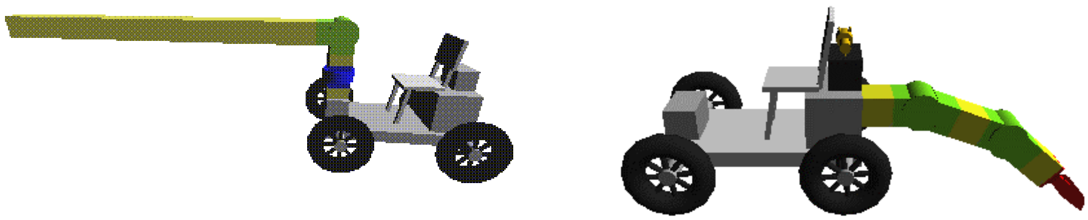


a) Robot A
Base: 102
Power: 001
Arm: 203,311,202,205,307,201,204,302,401

b) Robot B
Base: 102
Power: 003
Arm: 203,311,202,205,307,201,204,302,401

Figure 3: Short-Range Manipulation Robots

Figure 4 shows two robots (C & D) with dramatically different capabilities compared with Robots A & B. Both Robot C and Robot D use the #103 base module. Because of the larger wheel diameter this module is more mobile than the previous (#002) base and can provide mobility for one astronaut. Robot C is a crane-like robot with a maximum lifting capability of 175 kg. It has 2 joints that rotate about a vertical axis (#206), and a horizontal axis (#203). It has a 4.71-meter reach. This robot is well suited for obtaining rock samples from a high cliff face, or lifting objects from a high place on the lander. Robot D has two strong joints (#203) that operate in a plane. It has a maximum lifting capability of 412 kg and a scoop, or bucket, for an end-effector (#403). This robot would be capable of digging into the soil for science samples.



c) Robot C
Base: 103
Power: 001
Arm: 206,203,310,310,310,310,310,310

d) Robot D
Base: 103
Power: 001
Arm: 203,310,203,403

Figure 4: "Heavy" Manipulation Robots

Robots E and F are shown in Figure 5. These robots are designed to support human exploration. Robot E has a strong arm (maximum lift=388 kg., maximum reach = 2.12 meters), but because of the configuration of the joints, it can only operate in a plane. In this instance, the mobile base would be needed to move the manipulator outside this plane. Robot F also has a strong arm and a long reach (maximum lift=326 kg., maximum reach = 2.53 meters). However, this robot has a much more dexterous kinematic configuration. It could be used for more complex tasks such as instrument assembly.

e) Robot E
Base: 103
Power: 001
Arm: 310,203,309,311,305,202,302,201,401

f) Robot F
Base: 103
Power: 001
Arm: 206,203,311,205,202,307,201,205,201,401

Figure 5: Long-Range, Dexterous Manipulators

These six robots give an example of the distinctly different robot capabilities that can be produced from the module inventory. They represent a wide variation in operational parameters that can perform a wide variety of tasks.

5.2 Task 1: Soil Manipulation

The first task is the manipulation of large amounts of Martian/Lunar soil. This may be required for in situ resource utilization, burying a radioactive power generation unit, solar radiation protection, or preparing ground for construction/deployment of instruments. A robot was constructed form the modular inventory that is similar to a front loader, Figure 6. A manipulator is created with two strong joints (#203) and blade/scoop end effector (#405). The manipulator is attached to a one-person mobility unit (base module). This robot could be programmed to operate autonomously, tele-operated, or directly driven.

To manipulate soil the robot will need large traction forces. This requires good soil tire interaction and a massive vehicle. Vehicles with large mass are contrary to overall mission constraints. For this reason, this robot my require a drawbar and wench (module #404) to generate the required forward motion on soft soil. This complex interaction was not modeled for this phase I study.

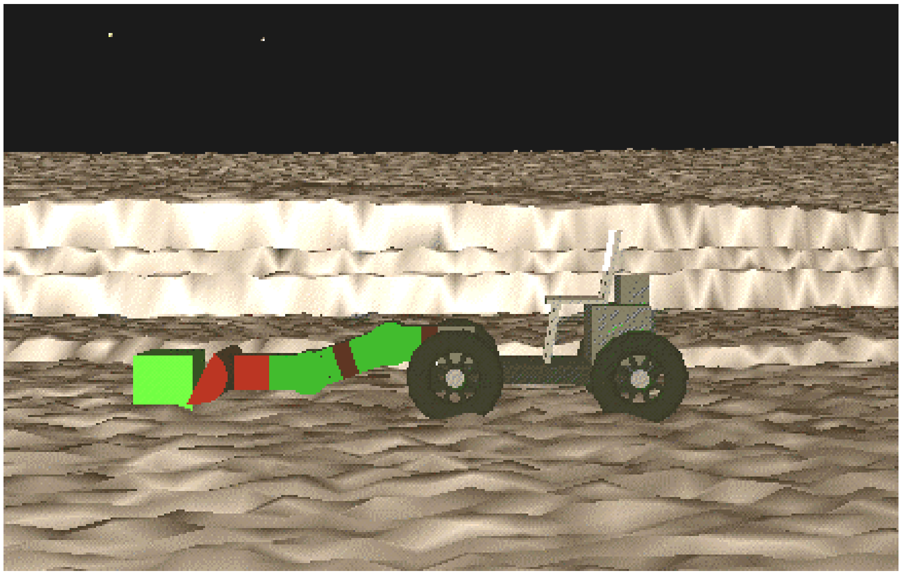


Figure 6: Robot "Front Loader"

The animation shows the robot lower the front loader, move forward, and make contact with the rock (green box). Then the robot pushes the rock out of view.

5.3 Task 2: Instrument Deployment

The second robot is simulated deploying a science instrument from a lander, Figure 7. This robot has a long and dexterous 4 joint manipulator attached to the #102 mobile base. The long reach may be required to remove the instrument from the high lander (the decent engine may require the lander to be tall) or to place the instrument in a difficult location (side of a cliff). The mobile base uses 4 outriggers for stability and can move up to 1 km to deploy the instrument.

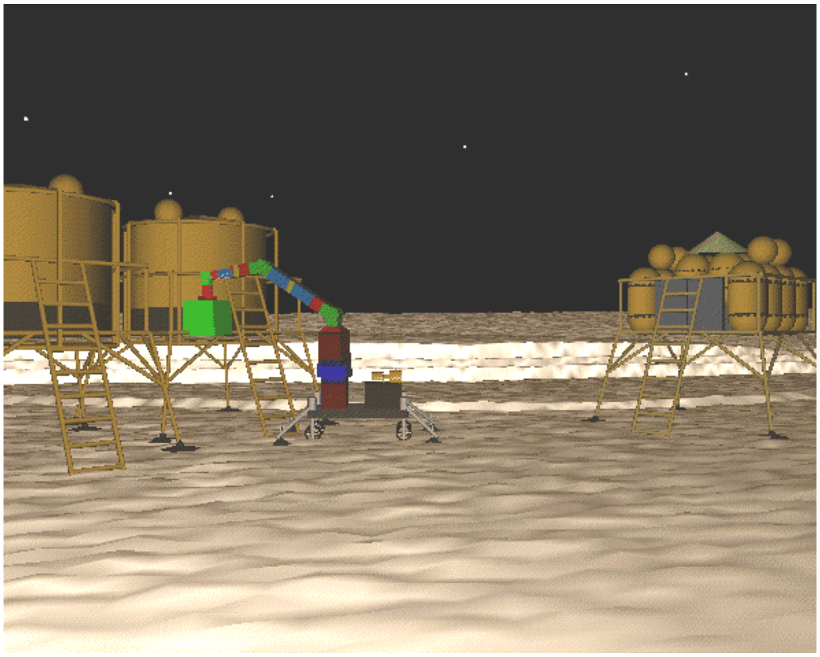


Figure 7: Crane-like "Deployment" Robot

The animation shows the robot approach the lander, deploy the outriggers, and grasp the instrument (green box). The manipulator then moves the instrument to place its mass to a stable location (inside the wheel base) and raises the outriggers. Then the robot moves to a new location and deploys the instrument in the reverse order.

5.4 Task 2: Scientific Sampling / Digging

The third robot is similar to a small backhoe, Figure 8. This robot would be used to obtain science samples and to dig into the surface to find these samples. The robot has a 4 joint manipulator with a scoop, or bucket (#403), as an end effector. The manipulator is attached to the rear of the same one-person mobility base module shown in the "front loader" robot (Figure 6). This base is capable of traveling up to 10 km from the outpost and would greatly improve the scientific exploration capabilities. Again, this robot can be operated autonomously, tele-operated, or directly driven.

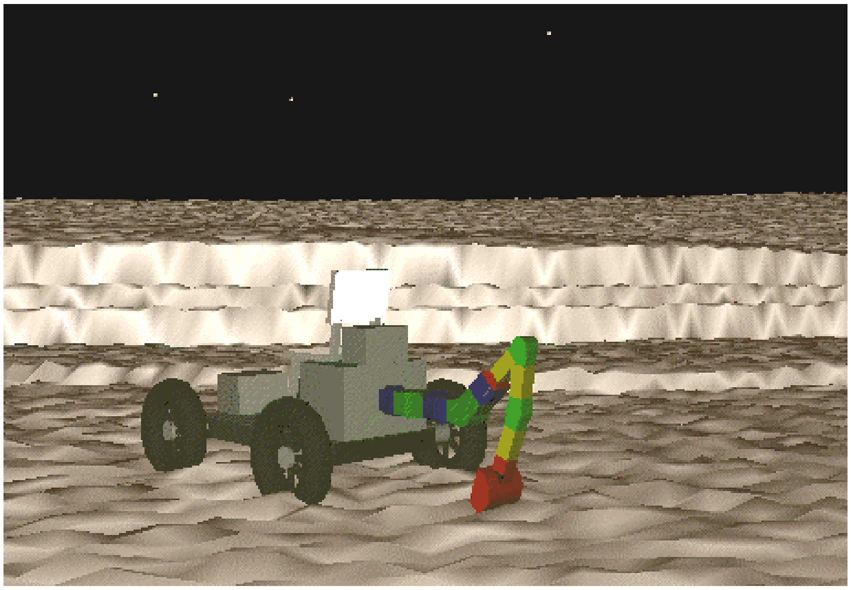


Figure 8: Robot "Science Sampler"

The animation shows this robot pushing the scoop into the ground with a digging motion, lifting the soil, moving the scoop to the side, and finally inverting the scoop to dump the soil. The robot then moves forward and repeats the process.

These three robots give an example of the distinctly different robot capabilities that can be produced from the module inventory. The phase I study showed the advantages in launch mass and launch volume as well as adaptability and reliability of the concept. The benefits in performance and the feasibility of the concept have been shown. This phase II study will further develop the concept and "deliver" complete mission scenarios (for both human exploration and a robot colony) for NASA's consideration.

6 Summary

Much was accomplished during this six-month phase I project beginning with a study of NASA's current mission scenarios. Knowledge of these mission plans was required to identify representative robot tasks. From the mission scenarios design specifications were developed and these specifications then used to design a modular inventory. This inventory was used to create specific robots that perform representative mission-relevant tasks.

Nine robots were described as examples of the diversity of robots (and capabilities) that can be produced using this approach. All nine robots were constructed using only 26 modules. Three of the robots were simulated performing representative, mission-relevant tasks.

The first simulated task shows a "front loader" robot used to manipulate large amounts of soil. This robot could be required for in situ resource utilization, burying a radioactive power generation unit, solar radiation protection, or preparing ground for construction/deployment of instruments. The second task showed a crane-like robot deploying a science instrument. The robot removed the instrument from a stowed position high on the lander and transported it to its deployed location. The third task simulated a robot digging for science sample. This robot could be used to support long-range (10 km) human exploration.

All results presented in this report were obtained during the six-month study. The simulation and animation were written from scratch. No previous results, from other studies, were included.

7 Conclusions and Future Work

The objectives outlined in the phase I proposal were accomplished. The Phase I study has demonstrated the scientific feasibility of the modular concept using detailed physical simulation. It was shown that a modular system could accomplish a wide variety of tasks that would normally require numerous traditionally designed robots. The phase I study showed advantages in launch mass and launch volume as well as adaptability and reliability of the concept.

Future work will include publication of Phase 1 work and results in technical journals. The work will continue to be developed into a graduate student thesis.

The phase II study will further develop the concept and "deliver" complete mission scenarios (for both human exploration and a robot colony) for NASA's consideration. Detailed plans for future work are given in the phase II proposal.

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Appendix A: Simulation

The robots were studied with computer simulations that considered physical constraints such as limb interference, geometric limitations, static stability, actuator saturation, and power consumption. The simulation was developed so that any robot made from the module inventory could be easily simulated. Because the robots travel at very slow speeds, dynamic effects could be neglected and the simulation uses a quasi-static analysis. The objective of the simulation was to determine if the robots could successfully perform the task.

A four-wheel rigid robot will not rest evenly on general Martian terrain. To determine the position of the robot some wheel compliance is assumed at each contact point, as seen in Figure 9.

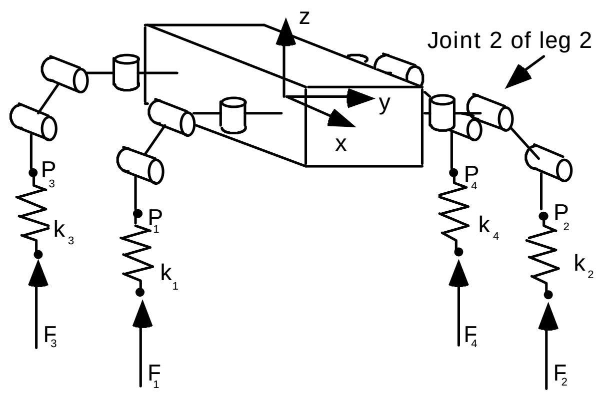

Figure 9: Calculation of Reaction Forces (figure from Farritor, 1998)

Here it is assumed that the surface is relatively level so slip and tangential forces are not an issue. The analysis would need to include a model of the frictional interaction between the feet and the environment in the more general case, this is beyond this six-month study. In this analysis it is assumed that the elements of the robot are rigid and the configuration of the robot at all instances is known (from kinematic analysis).

The added compliance along with the assumption that the robot is a rigid body allows the problem to be solved from static equilibrium.

$$\sum F_z = 0 : \; F_1 + F_2 + F_3 + F_4 - W = 0 \qquad (1)$$

$$\sum Mx = 0 : -F_1 y_1 + F_2 y_2 - F_3 y_3 + F_4 y_4 = 0 \qquad (2)$$

$$\sum M_y = 0 : -F_1 x_1 - F_2 x_2 + F_3 x_3 + F_4 x_4 = 0 \qquad (3)$$

$$F_n = k_n d_n \qquad (4)$$

Where d_n is the compression of spring n, W is the weight of the robot, and x_n, y_n and z_n are the wheel position defined with respect to the center of mass of the robot in its instantaneous configuration. The geometric constraint that the robot is a rigid body gives a fourth equation relating d_1 to d_4. For instance if the robot is walking on a flat surface all of the robot's feet must lie in a plane. This constraint is given by (5).

$$A(x_4 - x_1) + B(y_4 - y_1) + C(z_4 - z_1) = 0 \quad (5)$$

Where A, B, and C are the parameters of a plane defined by the foot positions P_1, P_2, and P_3. This leaves four equations and four unknowns. This can be used to determine the location of the vehicle on the rough surface of the Martian terrain. The wheel reaction forces can be used with a soil model to determine tire slip.

Power consumption is one of the performance factors considered by the simulation. Power consumption is estimated assuming the actuators are the dominant power consuming elements in the system (Dubowsky *et al.* 1994). With these assumptions, the power consumed is proportional to the square of the current drawn. For dc motors, this current is proportional to the applied torque. For the systems considered, it can be shown that the joint torques required to statically support the system dominate any dynamic effects (Dubowsky *et al.*, 1994). Therefore, to estimate the power consumption, the joint torques need to be computed. To do this, the endpoint reaction forces are found.

With knowledge of the manipulator endpoint forces, the joint torques can then be calculated. Figure 10 shows a typical manipulator in the static analysis.

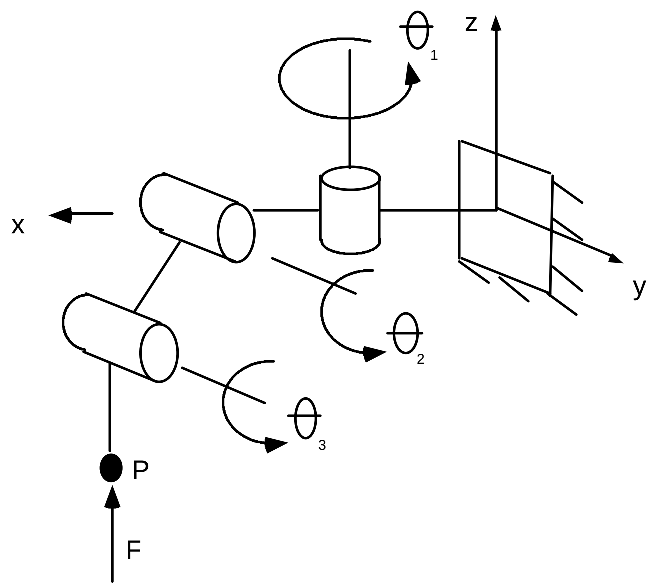

Figure 10: Calculation of Joint Torques of a Typical Manipulator

The torques at the joints are related to the reaction force, F, by:

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = \left[J(\theta_1, \theta_2, \theta_3) \right]^T \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \quad (6)$$

Where $[T_1, T_2, T_3]$ is a vector of the joint torques, J is the Jacobian of the limb, and $[F_x, F_y, F_z]$ is a vector of the reaction forces at the foot (Asada and Slotine, 1986).