An Astronaut Assistant Rover for Martian Surface Exploration

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Abstract

Lunar exploration, recent field tests, and even on-orbit operations suggest the need for a robotic assistant for an astronaut during extravehicular activity (EVA) tasks. The focus of this paper is the design of a 300-kg, 2 cubic meter, semi-autonomous robotic rover to assist astronauts during Mars surface exploration. General uses of this rover include remote teleoperated control, local EVA astronaut control, and autonomous control. Rover size, speed, sample capacity, scientific payload and dexterous fidelity were based on known Martian environmental parameters, established National Aeronautics and Space Administration (NASA) standards, the NASA Mars Exploration Reference Mission, and lessons learned from lunar and on-orbit sorties. An assumed protocol of a geological, two astronaut EVA performed during daylight hours with a maximum duration of four hours dictated the following design requirements: (1) autonomously follow the EVA team over astronaut traversable Martian terrain for four hours; (2) retrieve, catalog, and carry 12 kg of samples; (3) carry tools and minimal in-field scientific equipment; (4) provide contingency life support; (5) compile and store a detailed map of surrounding terrain and estimate current position with respect to base camp; (6) provide supplemental communications systems; and (7) carry and support the use of a 7 degree-of-freedom dexterous manipulator.

Introduction

As the National Aeronautics and Space Administration (NASA) turns toward interplanetary exploration[1], it is obvious that further innovations in and improvements to astronaut tools, transports, procedures, and life support systems must be pursued. Lunar exploration, recent field tests, and even on-orbit operations suggest the need for a robotic assistant to the astronaut during extravehicular activity (EVA) tasks. A robotic rover assistant would greatly reduce astronaut fatigue and increase productivity by performing time consuming, fatiguing, and repetitive dexterous tasks, which are made more difficult when working against the pressurized suit necessary for life support in any extraterrestrial environment. The assistant would also relieve the astronaut of carrying tools, scientific instruments, and samples. In addition, the rover could carry backup life support gear and supplemental communications systems, increasing the safety of EVAs. The focus of this paper is the summary of a semester long graduate project of the design of a robotic rover to assist EVA astronauts during Mars surface exploration. The overall design objectives of the EVA assistant are covered as well as a description of the subsystems. The ways in which the rover assists the EVA crewmember are also discussed. A detailed description on the design can be found in “Design of an Astronaut Assistant Rover for Martian Surface Exploration.”[2]

Design approach

The design of this rover utilized an iterative approach, with three groups initially considering three preliminary missions. Analysis of the resulting designs led to formation of mission assumptions, design scenarios, and design requirements for the final vehicle. This approach was selected to rapidly narrow down mission requirements, to consider widely varying missions, and to provide a reasoned basis for the selection of requirements of the final rover.

The mission requirements for the preliminary designs were:

- Support two astronauts on four hour EVAs
- A four hundred day useful life-time
- Rover capable of astronaut-traversable terrain -0.3 m obstacles with a maximum astronaut speed of 4 kilometers per hour (kph)
- Carry EVA tools and contingency life support

The three designs differed in the geological packages they supported and their ability to carry astronauts.

The smallest vehicle, the single arm assistant shown in Figure 1, carried a single dexterous arm for obtaining geological samples, carried 75 kilogram (kg) of samples out of a total mass of 760 kg, required 960 watts (W) average power, and did not have the ability to carry the astronauts.

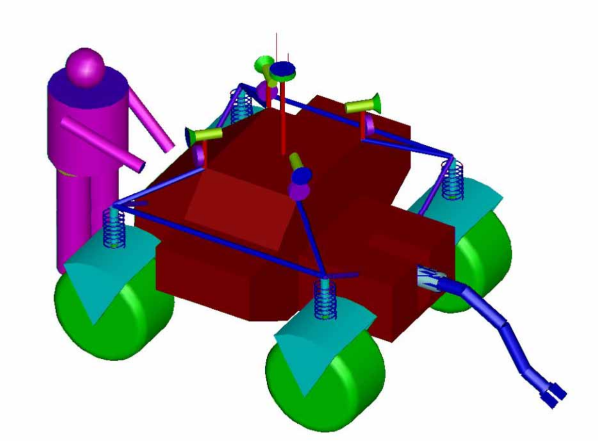

Figure 1: Single arm assistant

The second vehicle, or dual arm assistant shown in Figure 2, carried a pair of dexterous arms for geological sampling, carried 370 kg of samples out of a total 700 kg mass, used 1 kW average power, provided a degree of modularity by trading battery packs for sample storage containers, and could carry a single EVA subject in a contingency.

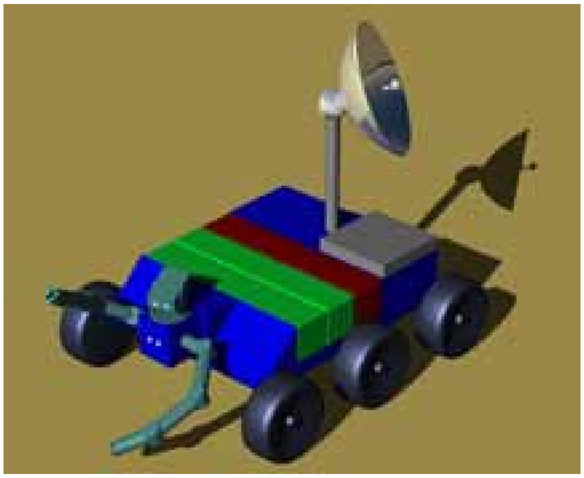

Figure 2: Dual arm assistant

The final vehicle, the large manipulator assistant shown Figure 3, supported a large positioning manipulator that positioned a pair of dexterous arms, had over 1,700 kg in mass, used over 4 kW of power on average, and was designed to carry the astronauts to and from the exploration site.

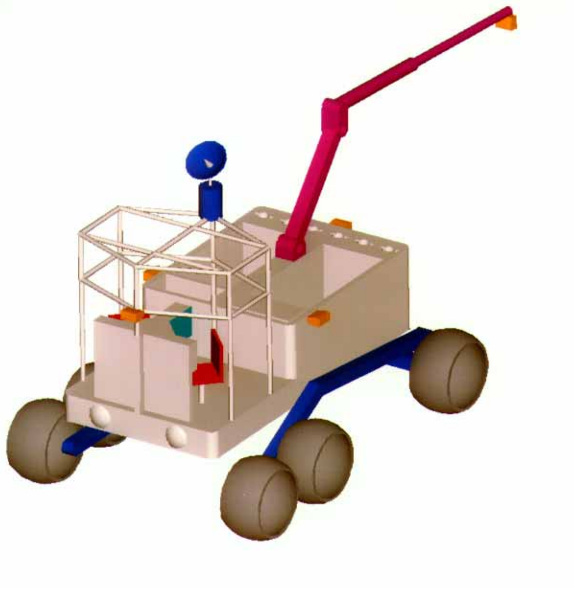

Figure 3: Large manipulator assistant

Based on the resulting designs, assumptions were made for the mission, mission objectives were prioritized, design scenarios were selected, and the design requirements were finalized.

Assumptions

In order to establish specific design requirements, reasonable assumptions must be made regarding EVA protocol, working environment, desired functionality, size and weight of the vehicle. In this design, there are three general uses of the rover: remote teleoperated control, local astronaut control, and autonomous control. It is assumed that EVAs occur only during daylight hours, are conducted by two astronauts, have a maximum duration of four hours, and do not exceed a 6-km radius from the base camp. It is assumed that satellite images of the Martian terrain are available to the crew for EVA site selection and area mapping with resolution worthy to be used by the rover during autonomous EVAs. It is further assumed that the rover is operated in the Martian temperate zones and is not required to traverse terrain that can not be traversed by a suited astronaut. For purposes of this design, the largest obstacle an astronaut on Mars can cross is 0.45 meters and the maximum terrain slope that can be traversed is 20 degrees. Further, the maximum speed an astronaut can maintain over level unbroken ground is assumed to be 4.8 kph, which drove an assumed rover maximum speed of 8 kph. It is also assumed that one component of a human Mars mission is to deploy small, permanent, scientific packages, or Deployable Instrument Packages (DIPs), on the surface of Mars. It is assumed that these self-contained packages may contain instruments such as barometers, anemometers, thermometers, or seismometers with a mass of 20 kg and dimensions of 40 centimeters (cm) by 40 cm by 20 cm. The rover also carries a 7 degree-of-freedom (DOF) dexterous manipulator for geological sampling, which is provided as a pre-integrated payload but depends upon the vehicle to provide power and intelligence. Finally, the size and mass of the rover is such that it meets functional requirements for scientific and carrying capabilities and yet is limited to accommodate small storage space, both on the transit spacecraft and at the base camp. A target vehicle mass and size of 300 kg and 2 cubic meters are set with the consideration that, in the event of a tumble, the astronaut is capable of righting the vehicle.

Design Philosophy

To assist in facilitating the iteration process, a design philosophy including prioritized objectives was established. Due to the harshness of the Martian environment, limited parts and resources available, and the rigorous performance demands on the rover, durability of parts and systems is considered the first priority. Second, in order to minimize launch costs, propulsion, and power requirements, and to allow astronaut manipulation in case of emergency, the vehicle is required to be lightweight. Third, the rover and its capabilities are tightly integrated into the daily tasks of astronauts working on Mars. Because the rover is used in an environment far from Earth nearly everyday for an extended period of time, it must be easily repaired and maintained. The design of all subsystems is such that the EVA Assistant is able to perform back-to-back sorties with minimal refurbishment and can receive any necessary servicing easily during "stand down" periods. This servicing is done in a pressurized volume at base camp and can be done in parallel to the servicing of the space suits between sorties. All subsystem trade studies and component decisions were made based on mission demands, functional requirements, and this priority outline.

Design Scenarios

To adequately determine design and functional requirements, it is necessary to consider specifically how the vehicle is used. The following are samples of detailed design scenarios used to illustrate the range of rover applications as well as depict expected worst-case situations for various aspects of the rover. Table 1 summarizes the requirements and rover configurations for each scenario

Scenario 1

The rover is either teleoperated from base camp or preprogrammed using satellite maps to travel to a potential EVA site. Because there is no astronaut accompanying the vehicle, it may travel at maximum speed to the site. Taking a similar route to and from the site, it is estimated that the rover will travel 1.5 hours one way (three hours round trip). Of that three hours, one hour of travel is spent traversing +/- 3 degree slope terrain (30 minutes at +3 degrees, 30 minutes at -3 degrees), and a minimum of 20 minutes are spent on +/- 20 degree sloped terrain (10 minutes at +20 degrees, 10 minutes at -20 degrees) at a maximum speed of 4.8 km/hr. The remainder of the travel time is spent traversing level ground. Once the rover reaches the site, functions such as mapping, full video survey, and sample retrieval are employed as needed. The dexterous arm is expected to be in use for 60 minutes and may retrieve pre-designated or directed samples through teleoperation, use an already deployed DIP to perform scientific experiments, or a variety of other tasks. Human factors equipment is not necessary for this mission and is therefore removed to save mass and subsequently lower power requirements. Throughout the scenario, however, navigation, mapping, and video/telemetry communications are used.

Scenario 2

Following Martian landing, the rover may be required to perform contingency operations within the immediate area of the base camp while the astronauts are adjusting to Martian gravity. It is assumed that the site for base camp is pre-selected for large open spaces, so the terrain can be considered mild and unthreatening. Rover locomotion requirements amount to an estimated 30 minutes at maximum speed on zero grade terrain. The rover is fully configured, excluding human factors equipment (tools, contingency life support and other interfaces). The rover must carry minimal tools and necessary end effectors for use by the dexterous arm. Full video is required to adequately maneuver to the site and manipulate the dexterous arm. The estimated time required for arm operations is 3 hours at average power.

Scenario 3

Many tasks, such as deployment of DIPs or beacons to remote sites, can be accomplished through teleoperation or autonomously by the rover, eliminating the need for a human EVA excursion. The terrain stipulations are much like scenario 1 in that the parameters of maximum speed, slope encounters during travel, and time of traverse remain the same. However, for this scenario, the rover has all unnecessary systems and interchangeable modules removed and carries only 20 kg of DIPs out to the site. At the site, the payload is deployed, resulting in an estimated 30 minutes of arm operations. It is assumed that the DIP starts operations independent of the rover or with minimum interaction. When the DIP is delivered to the site, the rover then returns to base camp free of payload. Communications, navigation, and mapping capabilities are required throughout the scenario.

Scenario 4

One of the greatest benefits of the rover is its ability to act as a geological/technical assistant during human EVAs. The rover travels at 4.8 kph for two hours including one hour on a +/- 3-degree slope and 20 minutes on a +/- 20-degree slope. The residual two hours of the sortie are spent at 1.6 kph for one hour at on level grade and one hour at rest. The rover is configured for full human factors support, prepared with a full science payload, powered for 30 minutes of arm operations and equipped to carry 12 kg of collected samples, of which up to 10 kg can be collected by the arm and up to 2 kg personally by the astronaut. The guidance, navigation, and control (GNC) system keeps current position estimated at all times to enable "fetch" and "lead home" commands, as well as terrain mapping. This scenario is by far the most demanding on all of the subsystems and can be considered a worst-case estimate of the performance requirements for many subsystems. Tasks such as core sampling, payload deployment, and extensive, widespread sampling may be designated through colored markers (see Markers) left by the astronaut during the sortie. After the astronaut returns to base, the rover may be sent to complete the designated tasks by teleoperation or autonomously.

Scenario 5

The final scenario is one in which a DIP is not fully automated or independent of the rover, and requires human assistance during deployment. The same terrain and traverse profile of scenario 4 applies to this mission. During the one hour at rest, the dexterous arm will perform approximately 30 minutes of operation. The rover carries contingency life support and necessary tooling. No scientific payload (excluding the DIP) or sample storage and support are required. The DIP contributes 20 kg of mass on the journey to the site.

Design Requirements

The following design requirements were developed based on the assumptions and scenarios outlined above.

Terrain

- Maximum speed of 8 kph over flat Martian terrain.
- Forward and lateral operation capabilities on a 20-degree maximum slope.
- Obstacle clearance of 45 cm, comparable to allowed Martian suit mobility.
- Accompany astronaut on 4-hour sortie with battery capacity for a total of 8 hours, or quick change out of 4-hour battery block, each day, six days of the week for four hundred days.

Payload

- Retrieve, label, catalogue, and carry 12 kg of collected samples from the EVA site back to base camp.
- Carry and support one 7 DOF dexterous manipulator to assist astronaut with difficult and fatiguing tasks.

Table 1: Scenario summary

Scenario	Control	Terrain/ Locomotion Requirements	Arm Operations	Rover Configuration
1	Teleoperation/ Autonomous	3 hours at maximum power • 20 min: +/- 20 degree grade (4.8 kph) • 1 hr: +/- 3 degree grade (4.8 kph) • 1 hr 40 min: 0 degree grade (8 kph)	1 hr	2 kg samples No human factors
2	Teleoperation/ Autonomous	30 min: 0 degrees (8 kph)	3 hrs	Min tools Min science No human factors
3	Teleoperation/ Autonomous	3 hours at maximum power • 20 min: +/- 20 degree grade (4.8 kph) • 1 hr: +/- 3 degree grade (4.8 kph) • 1 hr 40 min: 0 degree grade (8 kph)	30 min	Min science DIP (20 kg) No human factors
4	Supervisory	2 hours • 20 min: +/- 20 degree grade (4.8 kph) • 1 hr: +/- 3 degree grade (4.8 kph) • 40 min, 0 degree grade (4.8 kph) 1 hr: 0 degree grade (6 kph) 1 hr: rest	30 min	12 kg samples Full science Full human factors
5	Supervisory	2 hours • 20 min: +/- 20 degree grade (4.8 kph) • 1 hr: +/- 3 degree grade (4.8 kph) • 40 min, 0 degree grade (4.8 kph) 1 hr: 0 degree grade (6 kph) 1 hr: rest	30 min	Min science DIP (20 kg) Full human factors

- Carry astronaut hand tools necessary to meet mission objectives.
- Provide two hours of contingency life support for two astronauts (it is assumed that the astronauts will never exceed a two hour traverse by foot- approximately 6 km -from base camp).
- Carry instrumentation to support minimal in-field scientific testing of atmosphere, soil and geological patterns.

Autonomy

- Basic obstacle avoidance capabilities contingent to following the astronaut through the rocky Martian terrain.
- Track two astronauts at all times, employ safety measures to avoid contacting the astronaut at any time, and relay video to base camp for additional safety.
- Maintain a current position estimate with respect to base camp at all times to enable "fetch" (rover returns to base, acquires necessary items, and returns to the field site autonomously) and "lead home" (guide astronauts back to base camp) commands.

Rover design

The final rover design, shown in Figure 5 and Figure 6, incorporates a rocker-bogie suspension, a dexterous arm placed on the front, all EVA related tools and equipment on the rear, and a centrally located arch support to elevate cameras and antennas. The vehicle body is 1.5-m long, 1.0-m wide, and 0.25-m high, with a 0.5-m ground clearance.

The vehicle's mass budget is shown in Table 2 and, depending on the scenario, ranges from a little over 220 kg to almost 300 kg. This is within the vehicle design requirements and shows the heavy dependency upon the specific scenario. The power requirements are also heavily dependent upon the scenario, and are shown in Table 3.

Subsystems

An overview and brief summary of each of the rover subsystems is given in the following section. A more detailed account of these subsystem designs, including trade studies and optimization, can be found in "Design of an Astronaut Assistant Rover for Martian Surface Exploration."[2]

Science Payload

The Science Payload supports Martian optical terrain studies, geological surveys and sample collection, seismology and meteorology data collection, and minimal in-field sample testing.

Optical terrain studies are carried out using a panospheric, omni, and stereo camera; a 24X telescope; an infrared camera; and a small camera mounted on the manipulator arm. The panospheric camera uses a hyperbolic lens, enabling a full 360-degree view of the surrounding terrain. The stereo camera is a pan and tilt unit (PTU) that may be controlled either from base camp during teleoperation mode or by the EVA astronaut through a remote control pendant (see Manual Control of the Assistant). The telescope is essential during EVAs to allow astronauts to evaluate a sight removed by some distance before executing a long and fatiguing traverse. The infrared camera provides data about Martian landscape temperatures and potential geologic activity. Output from the small camera mounted on the manipulator arm can be accessed by the EVA astronaut or base camp to inspect more closely rock formations not accessible to the astronaut either because of height, accessibility, or distance.

The manipulator arm is a 7 DOF pre-integrated package that is 114 cm long, weighs 18 kg, and has an average power requirement of 10 amps (A) and 28 volts (V) and reaches peak power consumption at 21 A at 8 V. The arm is able to produce a tip force of 111 newtons (N). Figure 4 shows the 7 DOF manipulator arm without end effectors.

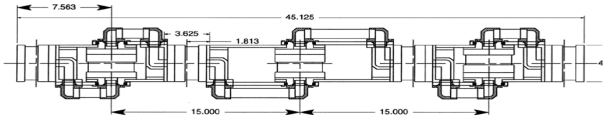

Figure 4: Manipulator arm

The arm autonomously swaps and stores interchangeable end effectors and utilizes a drive unit capable of activating grasping or rotary end effectors similar to the dexterous manipulators of the *Ranger*[3] neutral buoyancy vehicle used in the Space Systems Laboratory at the University of Maryland, College Park. One such end effector is the scooper/grasper that is able to retrieve 27 cubic cm of soil or larger rock samples. An impulse jackhammer is also included to break up rocks too big to retrieve or carry back to base

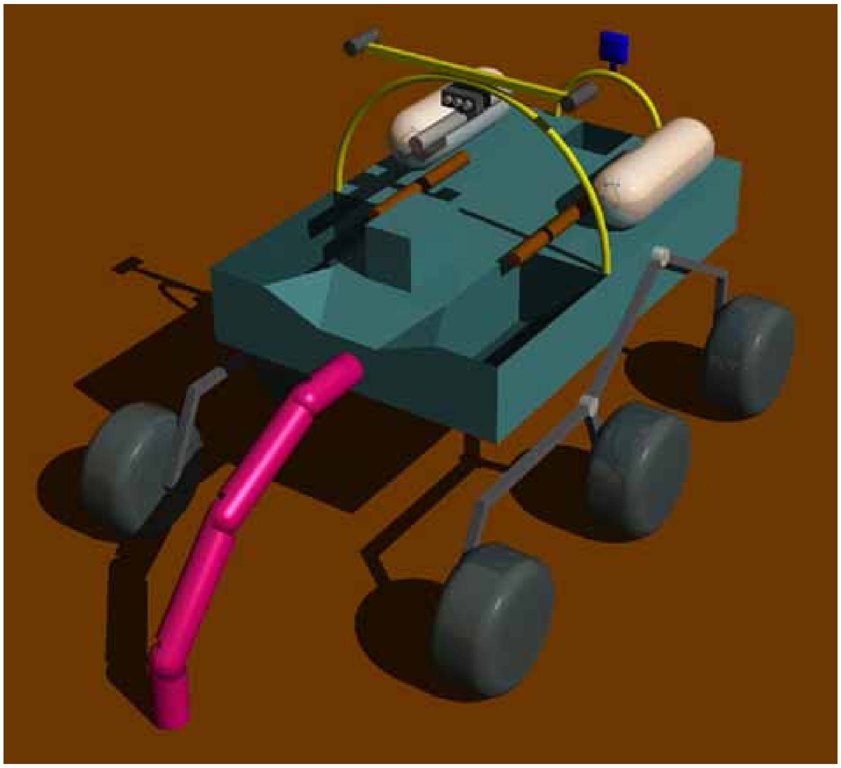

Figure 5: Fully configured EVA assistant

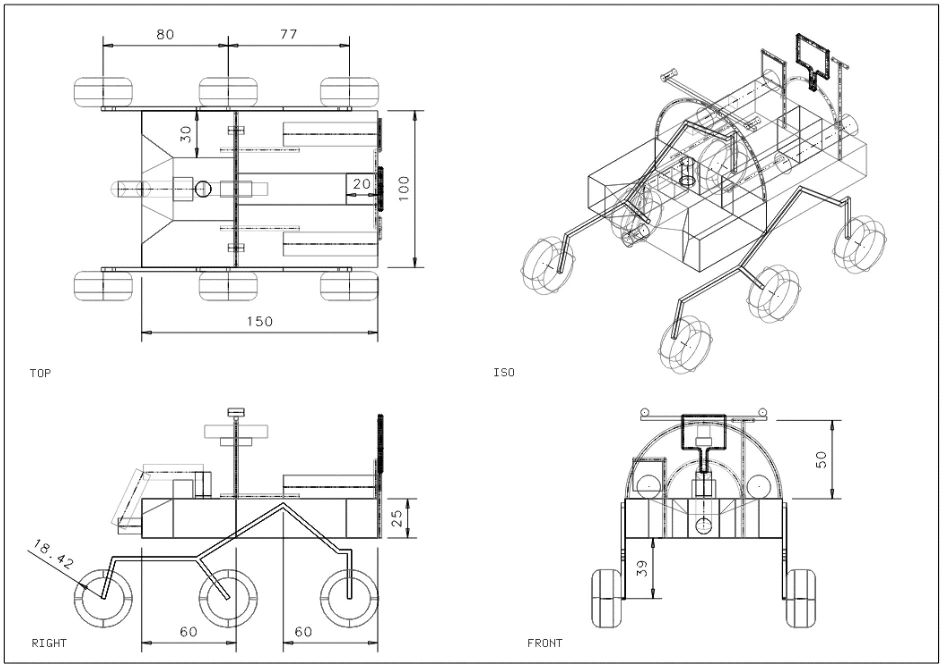

Figure 6: Dimensions of the EVA assistant

Table 2: Mass budget (all values in kg)

Subsystem	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Human factors	4	4	4	49	49
GNC	17	17	17	17	17
Communications	7	7	7	7	7
Science payload	44	29	49	54	49
Power	61	61	61	61	61
Thermal	1	1	1	1	1
Structure	30	30	30	30	30
Suspension	70	70	70	70	70
Total	**234**	**220**	**239**	**289**	**284**

Table 3: Power budget (all values in kg)

Subsystem	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Battery mass	**54**	**35**	**54**	**39**	**33**

so a sample may be taken. The arm is capable of deploying a core driller, which can take samples 3 cm in diameter and 0.5 meters (m) long. Astronauts designate sites for sample retrieval, DIP deployment, and arm operations through the use of marker flags, on-site remote control, voice commands, teleoperation, or pre-programmed autonomous control. All samples retrieved by the arm are placed and sealed in a bag on site and digitally marked and encoded with a bar code that can be linked to position, video, and other scientific data taken at the site of retrieval and placed in the main sample stowage bins. Samples retrieved by the astronaut receive the same encoding specific to the sample but are placed by the astronaut in a smaller sample stowage bin at the back of the vehicle out of manipulator arm workspace.

A 28X-180X microscope is provided when required by the EVA protocol to conduct in-field testing of samples. Adjustments to magnification, focus and other features is done via remote control. Optical feedback is given to the astronaut via video link.

All images collected, either through vehicle or arm mounted cameras, telescope, or microscope, are stored digitally on the rover and at base camp to minimize data loss.

Guidance, Navigation, and Control

The objective of this subsystem is simply to determine where the rover is, where it needs to go, and how to get there. The rover can perform autonomous and teleoperated navigation and mapping. Navigation is divided into two parts: global and local. Global navigation is going from base camp to the area of interest and back. It is composed of astronaut following (rover follows behind or beside the astronaut at a safe distance); autonomous navigation (final destination or path is specified and the rover must autonomously navigate); and teleoperated navigation (human operator drives the rover through an interface at the base or on-site). Local navigation is the process of obstacle avoidance that is performed by the rover and may be supplemented by a teleoperator. Mapping is composed of general terrain topography, and site and sample location recording.

The rover operates in several different modes — autonomous, semi-autonomous, teleoperated, manual, and voice command — each requiring different levels of functionality and performance. During *autonomous control mode*, the rover uses an on-board map from satellite images and referenced to the base camp to execute a mission to a pre-programmed site, perform necessary operations and return to base. *Semi-autonomous mode*, also referred to as “Follow Me” mode, allows the rover to follow the astronaut over Martian terrain. The rover is controlled from the base camp during *teleoperation mode* via a radio command link using the stereo camera PTU or omni cameras on the vehicle. The astronaut on site uses the control pendant to position the rover precisely or perform specific tasks during *manual control mode* (see Manual Control of the Assistant). Finally, *voice control mode* allows the astronaut hands