A Basic Utility Rover for Research Operations

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Abstract

Technology is advancing such that, in the not-too-distant future, Mars will be opened to human exploration. A robotic field assistant would improve an astronaut's ability to conduct surface exploration. This paper describes the Basic Utility Rover for Research Operations (BURRO), a 625 kg rover to provide such aid. The rover was designed to meet specified Given requirements while operating in the known conditions of the Martian environment. The system is able to: (1) drive over a 0.5 m obstacle; (2) carry a 200 kg astronaut, robot arms weighing 150 kg, and 100 kg of mission-specific payload; (3) carry a second astronaut in case of emergency; (4) maintain a 5 km/h speed through the duration of an eight hour traverse; (5) sustain a 10 km/h sprint for one hour; (6) be directly driven by an on-board astronaut, teleoperated, or operated in semi-autonomous or fully autonomous modes; (7) traverse up or down a 30º slope or perpendicular to a 20º slope; and (8) park parallel to a 45º slope or perpendicular to a 30º slope.

Introduction

In the next few decades, NASA and its partners will most certainly land humans on Mars for an extended exploratory mission. As the Apollo Lunar Roving Vehicle showed, it is helpful to have a transportation vehicle to assist astronauts in scientific exploration [1]. A robotic field assistant could carry instruments and samples, perform dexterous tasks with its robotic arms, and even transport the astronauts themselves, minimizing fatigue. In addition, a rover could autonomously take samples at previously identified sites while the astronaut continued to explore, enhancing the productivity of the extravehicular activity (EVA). Furthermore, the rover can accurately photograph and catalog the sample site, increasing the accuracy of the information being harvested. Different levels of autonomy and remote command allow the rover to explore areas uncharted or unsafe for humans. Our goal was to design a vehicle that could accompany astronauts to Mars and help them as much as possible. BURRO is shown in Figure 1.

Figure 1: BURRO

Design Approach

Given Requirements

The design for BURRO meets the following requirements:

- Carry one 200 kg astronaut, plus 100 kg of mission specific payload and two dexterous robotic arms weighing a total of 150 kg
- Accommodate a second EVA crewperson in case of emergency
- Be driven at 5 km/h for 8 hours
- Be driven at 10 km/h for 1 hour
- Climb and descend a 30º slope and drive across a 20º slope

- Remain statically stable while parallel to a 45º slope or perpendicular to a 30º slope
- Drive over a 0.5 m obstacle
- Be driven directly by an on-board astronaut, teleoperated, or operated in semi-autonomous or fully autonomous modes.

Derived Requirements

The specifications outlined above led to the development of further assumptions:

- All missions are performed by a pair of rover/astronaut teams
- All samples must fit inside the allotted science trays
- The base provides maintenance and storage facilities for the rover
- The batteries are rechargeable by the base power supply
- Both astronauts can successfully return to base in the case of one rover or one astronaut becoming incapacitated.

Martian Environment

Known characteristics of the Martian environment also drove our design, and are presented here [2]:

- Highly abrasive dust requires all moving parts to be sealed
- Temperatures ranging from -80ºC to 0ºC require systems to be thermally insulated
- Extremely low pressure requires astronaut life support systems
- Nighttime carbon dioxide frost requires electronics to be sealed and heated
- The terrain ranges from hard rock to drift material
- The gravitational field strength of Mars is 3/8 that of Earth.

Mass Budget

The total mass of a fully-loaded system is just under 1000kg (Table 1).

Table 1: Mass budget for BURRO

ELEMENT	MASS
Science Payload and Tools	30.2 kg
Wheels + Drivetrain (each)	45.0 kg
Frame (including suspension)	155.0 kg
Seat	24.0 kg
Robotic Arms	150.0 kg
Power and Thermal Control	140.4 kg
Scientific Payload (fully loaded)	100.0 kg
Astronaut + PLSS	200.0 kg
Total	979.6 kg

Design Scenarios

The design requirements and derived assumptions led to the development of a nominal mission and an emergency scenario.

Reference Mission

The reference mission describes nominal astronaut-rover operations. An 8-hour mission consisting of one-hour legs, each composed of forty minutes of travel followed by twenty minutes of scientific data collection. Three of these legs are up a 30º inclination, three are down the same slope, and two are across flat ground.

Emergency Scenario

The emergency mission is contrived to highlight the Given requirements, and is thus a worst-case scenario. This mission is proceeding normally, with the rover traveling for 4 hours at 5 km/h without science stops. At 20 km out, it turns around and starts back at the same speed. Having completed two more hours of travel, an emergency arises that requires a sprint back to base at 10 km/h.

Structure

Three things drove the structural design of BURRO. First, the rover had to fulfill all Given requirements. Second, the design should maximize functionality. Finally, the rover should be reliable and durable since spare parts will not be readily available. Vehicle layout focused on situating tools and instruments within the workspace of a space-suited astronaut. The astronaut can easily board the rover and ride in comfort. In addition, the astronaut’s seat is located at the front of the vehicle to provide maximum forward visibility. The deck space is all within arm’s length and provides substantial storage volume and work area. The robotic arms are attached to the rear of the vehicle to provide a large work envelope.

A square footprint was selected to provide vehicle stability in rough terrain. All large rover systems are located low in the body to enhance this stability. A 2.0 m length was selected to provide adequate clearance between the wheels and ensure sufficient structural volume for rover systems and payload. The main body section is tapered to allow for a 45º steering arc for each wheel. This feature, in conjunction with four wheel steering, adds the ability to turn in place, avoiding an obstacle directly in front of the rover. The main body section is 2 m in length and 1.6 m wide at mid-body, but tapers to 1.1 m between the wheels to the fore and aft.

Structural material selection was made in keeping with three priorities. First, the rover must be able to withstand a worst-case impact (0.5 m obstacle at 10 km/h) and maintain structural integrity. Second, the frame must be able to withstand continuous bending and vibrational loadings while in motion. Finally, the rover must be relatively light and easy to transport. Hollow 5 cm 7075 Aluminum was selected for its properties of high strength to weight ratio, adequate fatigue life, availability, and ease of manufacturing. Encasing the aluminum frame will be paneled shell built of a composite material.

Figure 2: Rover navigating 0.5 m obstacle

Suspension

The objective of the suspension is to maintain continuous contact between the wheels and the ground. This will provide efficient power transfer from the drive system and a stable ride. A trade study was conducted between the six-wheel Rocker-Bogey style of suspension and a four-wheel independent suspension system. Although the former has been used on recent Martian rovers, it is not readily adaptable to our larger, faster-moving vehicle. Although the Rocker-Bogey system has proven its ability to clear obstacles in excess of twice the diameter of the wheel, this capability has only been proven in quasi-static conditions. In contrast, a properly designed four-wheel independent suspension demonstrates good dynamic stability. In addition, the six wheels of the Rocker-Bogey suspension system add mass and complexity to the drive and control systems. As a result, a four-wheel independent suspension is implemented. Since the center of gravity has been located low on the vehicle, we are able to use a 1.1 m wheel diameter to clear the specified 0.5 m obstacle at design speed, as BURRO is shown doing in Figure 2.

The suspension damping system is tunable to provide an optimal ride in all terrain and loading conditions. This is accomplished through utilization of multiple sensors by the control system to determine the required damping coefficient and accordingly adjust the damping with a magneto-rheological fluid [3]. The suspension has 50 cm of total vertical deflection.

Wheels

As discussed above, the wheels have a 1.1 m diameter. The wheel width of 0.35 m was selected to accommodate the motor and geartrain internally while limiting wheel sinkage.

The design incorporates moderate compliance to achieve a number of performance goals. Compliance in the wheels aids traction and handling on hard surfaces and adds a small amount of additional suspension. The criteria for material selection were an extended fatigue life and a high strength to weight ratio. Woven IM7 carbon fiber was chosen for its small fiber diameter and high-density wrap, which mitigates the common failure modes of composite structures, namely delamination and matrix cracking. This material is resistant to the extreme temperature changes present in the Martial environment. The wheel tread is wrapped with Aramid fiber to increase traction and protect the wheels from puncture.

The basic shape of the wheel is a toroid, as can be seen in Figure 3, supported by an internal structure that is tapered to allow a 45º turning angle on the wheels.

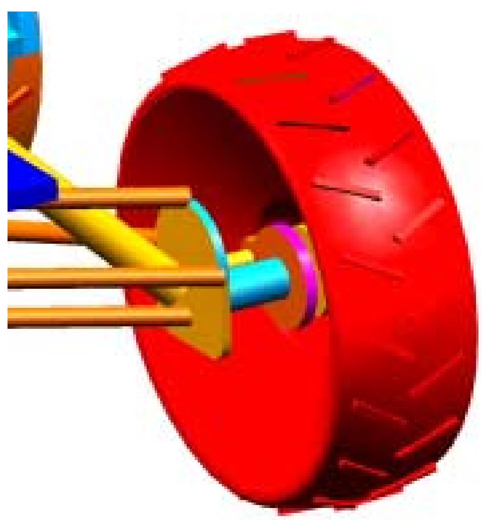

Figure 3: Wheel and suspension detail

Steering

BURRO employs full Ackermann steering to reduce dragging of the inside wheel, which helps maintain traction in turns. Full Ackermann steering is accomplished through independent actuation of each wheel. To minimize the torque required for steering, the kingpin axis is located at the center of the wheel. A linear actuator secured to the suspension drives a 30 cm steering arm to provide the necessary torque. This can be seen in Figure 4.

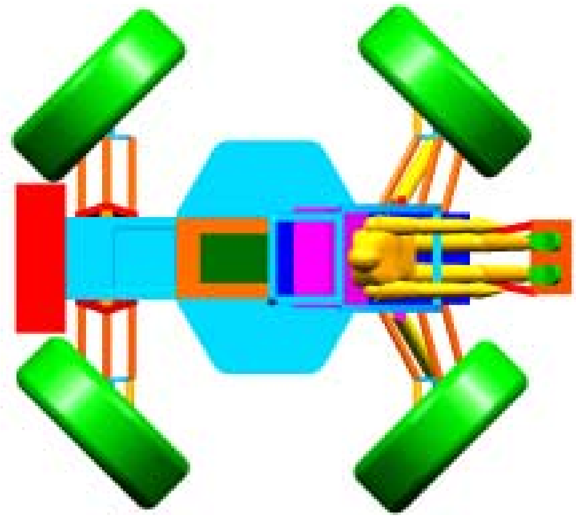

Figure 4: Four-wheel independent suspension

Brakes

We will use a regenerative braking system as our main source of stopping. The motors are run in reverse, which has the effect of recharging the batteries. We will also utilize an auxiliary parking brake, similar in design to that on a car, when the rover is stopped on a slope or in case of emergency. Braking software will calculate the force required to stop the motors based on the relationship between the current speed of the motor and the weight load on the rover.

Drivetrain Specification

The operating environment and the specifics of wheel geometry and loading drive the motor and drivetrain selection. For the purposes of this analysis, the operating environment is described by soil properties and terrain inclination. The general geometry of the wheel as outlined above will be used in this analysis. Finally, the wheel loading is influenced by the weight of the rover and varies as weight is transferred between wheels due to suspension action.

The soil on Mars varies from rock to a drift material similar to fine sand. The only broad category of soil unlikely to be encountered by the rover is mud. Thus strong parallels exist between soil types to be encountered on Mars and soil types that can be found on Earth. There are no inherent differences in the soil types between Earth and Mars that would preclude the application of standard soil description techniques to the Martian environment. In fact, many of the experimentally developed relationships used to describe wheel and soil interactions are most successful in predicting performance in dry soil types.

Empirical testing conducted by Bekker found the relationship for rolling resistance shown in equation (1).

$$R = \frac{0.87}{(b \times k)^{\frac{1}{2}}} \times \frac{W^{\frac{3}{2}}}{D^{\frac{3}{4}}}, \qquad (1)$$

where R is the rolling resistance in pounds-force, b is the wheel width in inches, k is the soil cohesion coefficient in pounds per square inch, W is the wheel loading in pounds-force, and D is the wheel diameter in inches [4].

Fortunately, the Viking probes performed the necessary tests to determine soil coefficients for the Martian environment. The soil types sampled by the Viking probes are divided into three basic types: drift, blocky, and rock. As expected, operation in drift produces the highest rolling resistance, since the soil cohesion is minimal.

The remaining variable for the rolling resistance equation is the wheel loading. Because the rover does always operate on level ground, the wheel loading is not limited to one quarter of the rover weight. In extreme obstacle clearance situations, a single wheel could support the majority of the vehicle weight. The worst-case scenario occurs when the rover attempts to navigate a large obstacle in loose soil. Combinations of wheel loading conditions and soil types were examined to produce a range of force requirements at different operating points.

One final characteristic of any terrain is inclination. A design requirement for the rover is the ability to traverse a 30º slope. Simple geometry dictates that, in the absence of rolling resistance, the wheels must be capable of producing a combined force equal to half the weight of the rover to fulfill this requirement. The total force required is the sum of the force required to lift the vehicle against the force of gravity and the force required to overcome rolling resistance.

Before specifying a drivetrain, the forces imparted by the wheels must be converted to torques. The required torque is the force required multiplied by the radius of the wheel. There are some insights to be gained from this simple relationship. The rolling resistance equation indicates that the required force application is reduced as the diameter is increased. Unfortunately, the torque required increases linearly with the radius of the wheel. The linear increase in the torque requirement outpaces the benefits seen due to the reduced rolling resistance. Since the force required for slope climbing is independent of soil conditions, the torque requirement will further increase in proportion to wheel diameter. The increase in required torque is offset by a reduced speed requirement for the wheel. However, since electric motors are inherently high speed, low torque devices, the reduced speed requirement is not a beneficial tradeoff [4].

It is important to carefully analyze the applicability of empirical formulas before drawing general conclusions. Taking Bekker's equation as a complete model of rolling resistance would lead to wheel designs with extremely small diameters and extremely wide treads. This would minimize both the rolling resistance and the required torque. However, Bekker's equation is only applicable in relatively low sinkage situations. Bekker characterized another effect, known as bulldozing resistance, which becomes dominant when the wheel sinks to a significant percentage of the diameter of the wheel. So, while the large wheel diameter is primarily dictated by the requirement to clear 0.5 m obstacles, even if that requirement were relaxed, the optimal wheel diameter would be determined by both the standard rolling resistance and the bulldozing resistance [4].

Motor and Drivetrain Specification

A brushless direct current motor coupled to a planetary geartrain represents the final design decision for the independent actuation of the wheels. This decision was reached after careful consideration of the attributes of both elements.

The brushless motor removes the need for physical commutation of the windings through brushes. Instead, the windings are incorporated into the stator and the motor is commutated electronically. Brushes traditionally represent a likely failure mode for the motor. In addition to simply wearing out, the erosion of the brushes can cause conductive dust to foul other components of the motor. The brushless motor removes this failure mode and provides the extra benefit of easier thermal control. Since the windings are in the stator, the heat generated by the electrical losses can be removed through heat sinks connected directly to the stator. In contrast, the heat generated in the windings of the rotor can only be removed through radiation directly from the windings and conduction through the bearings and brushes.

Gearing is required in the design to reduce the size and weight of the motor. As stated above, motors are inherently high speed, low torque devices. Gearing converts the motor mechanical power to a lower speed at a higher torque. A larger gear reduction results in a smaller motor size. However, large gear ratios are difficult to accommodate in the limited space of the wheel. The planetary gear design is capable of fairly large gear reduction within a small package. The harmonic gear design represents another option that obtains similar gear reduction for even less weight and volume. Unfortunately, harmonic gears require tighter tolerances and generally wear out faster than planetary gears. The robustness of the planetary gear design makes it an attractive option for the rover drivetrain.

A motor and a planetary gear were sized for the rover drivetrain based on the required torque and speed from the cases examined above. The final design incorporates a commercial off-the-shelf motor and a two stage planetary gear based on manufacturer specifications. The specific design of the planetary gear is not dictated here but requirements include output torque (500 Nm), input speed (3500 rpm), efficiency (85%), and gear reduction (36:1). Since an actual motor is specified for the design, it is possible to show the performance envelope of the rover based on the torque curve of the motor. The curve in Figure 5 represents the maximum continuous torque output of the motor as a function of the motor angular velocity. Also represented on the plot are a number of important operating points for the rover. These include both the design requirements as well as interesting values such as the top speed on a hard surface and the maximum slope that can be traversed in drift.

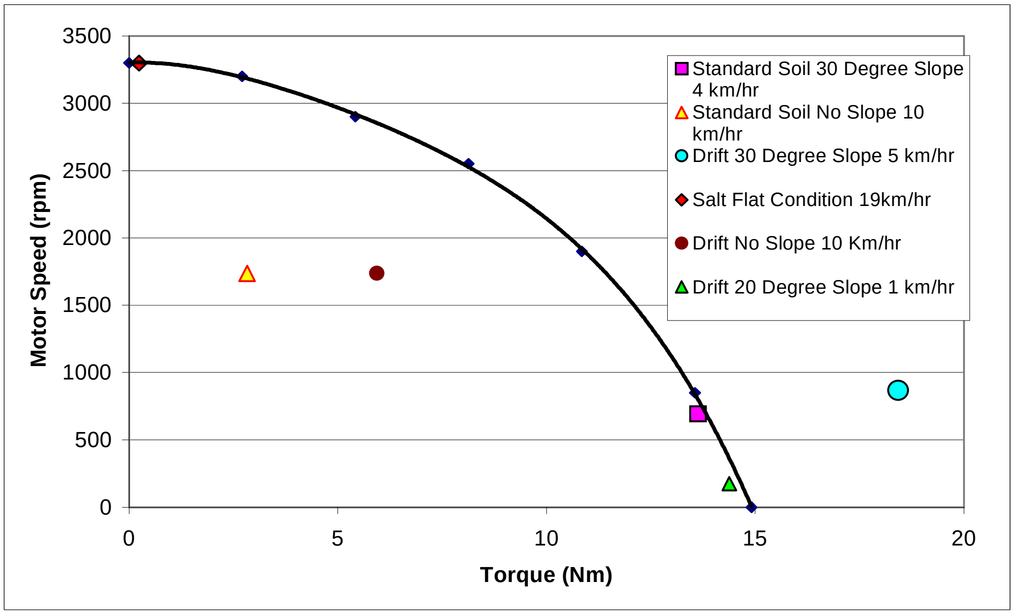

Figure 5: Motor operating curve

Figure 5 shows that the rover can easily handle flat ground situations. In fact, over flat terrain, the rover exceeds the speed requirement of 10 km/h. However, when the rover encounters a slope, the performance margin quickly erodes. The torque requirements rise dramatically due to both the requirements to lift a significant percentage of the rover weight as well as the effect of the suspension as weight is transferred to the rear wheels. This analysis indicates that the rover is barely capable of traversing a 30º slope on the blocky Martian soil but is limited to crawling up a 20º slope in drift. The limits shown in Figure 5 indicate that the drivetrain would benefit from a higher gear reduction, which would reduce the maximum speed while increasing the maximum torque capability of the system. However, planetary gear reductions in excess of 36:1 may require a special design.

Batteries and Electronics

Space-rated, lithium-ion batteries from Eagle-Pitcher were chosen to power BURRO as an example of commercially available battery technology. The battery dimensions are 16.99 cm length by 9.22 cm width by 21.92 cm height. Each battery weighs 8.89 kg and is capable of providing 170 Watt hours per kilogram of energy [5]. Several scenarios were examined to determine the required battery mass, with results given in Table 2;

1. Worst-Case: An 8-hour traverse at 4 km/h through standard soil; the first half of the trip is down a 30º slope, and the second half is back up the slope to base.
2. Given Speed: Maintain a speed of 5 km/h for a full 8-hour traverse across flat, drift-covered terrain.
3. Given Sprint: Maintain a speed of 10 km/h for a 1-hour sprint across flat, drift-covered terrain.
4. Reference Mission: The 8-hour mission previously described, in which the uphill traverses climb a 30º slope at 4 km/h through standard soil, the downhill traversals descend a 30º slope at 6 km/h through standard soil, and the flat legs are 5 km/h through terrain covered by drift material.
5. Emergency Scenario: This is the worst-case scenario outlined earlier in this paper.

Table 2: Energy Consumption for Different Scenarios

Scenario	Energy (overcome resistance due to soil compression) [4]	Energy (overcome effects of gravity)	Energy (power the electronics)	Total Energy (after 30% loss due to mechanical transmission)	Total Battery Mass Necessary	Total Number of Batteries Necessary
Worst-Case	1.14E+07 J	3.72E+07 J	1.44E+07 J	9.00E+07 J	147 kg	17
Given Speed	1.14E+07 J	0 J	1.44E+07 J	3.69E+07 J	60 kg	7
Given Sprint	3.56E+06 J	0 J	1.80E+06 J	7.66E+06 J	13 kg	2
Reference Mission	9.50E+06 J	1.49E+07 J	1.44E+07 J	5.54E+07 J	91 kg	11
Emergency Scenario	2.55E+07 J	0 J	1.26E+07 J	5.44E+07 J	89 kg	10

The worst-case scenario would suggest that this rover requires approximately 150 kg of batteries. However, this scenario is highly improbable. A more likely yet still conservative scenario is the reference mission, as all the uphill traverses involve a worst-case 30º slope and all flat travel is through drift material. After including a 30% safety margin to the total battery mass necessary, we find that loading the rover with fifteen batteries, for a total weight of 135 kg, will provide enough battery power for all likely missions. Figure 6 gives a graphical representation of the energy drained from the batteries over the duration of the reference mission.

The batteries are only operable between -5ºC and 30ºC. This motivated the design of a warm battery box (WBB), similar to the one aboard Sojourner, to keep the batteries warm in the extreme Martian temperatures [5]. This 71 cm long, 67 cm wide, and 52 cm high box will enclose the fifteen batteries arranged in a five-by-three-by-one array. The heat from actively-controlled, resistive heating strips will be contained by 10 cm of Silica Aerogel plus carbon black insulation. The heating strips can be turned off during the day when the ambient temperature is relatively warm, allowing heat stored inside to dissipate slowly.

The electronic components also need to be in a sealed box to protect them from the harsh Martian environment. It is assumed that the electronics will have an operating temperature range of -40ºC and 40ºC, similar to that of Sojourner. In order to keep the electronics warm despite the extreme Martian temperatures, a 20 cm by 30 cm by 40 cm warm electronics box has been proposed, which will be insulated with 5 cm of the same Silica Aerogel as the WBB and also contain actively-controlled resistive heating units [6].

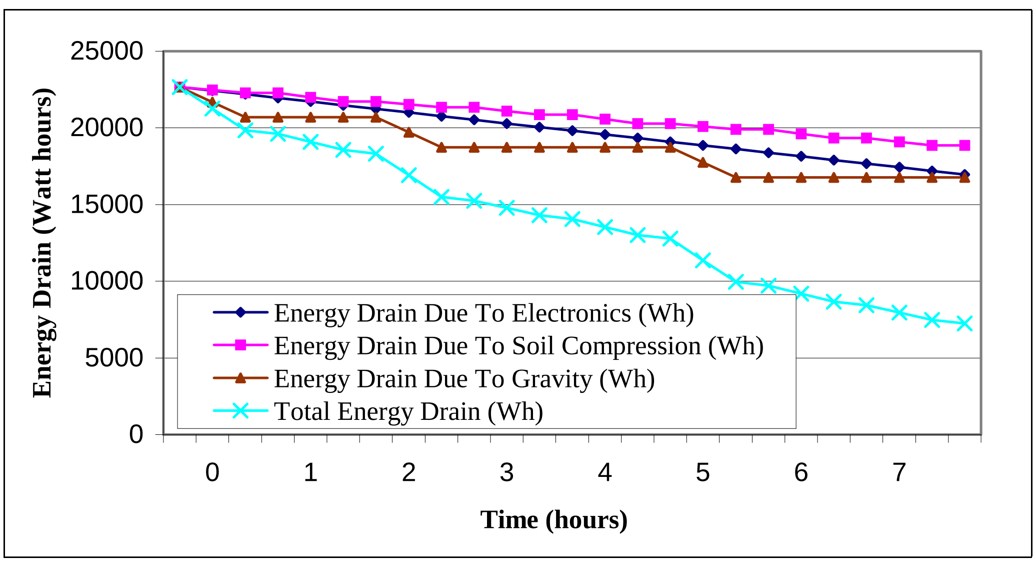

Figure 6: Energy drain from batteries through reference mission

Vehicle Control

The controls input system provides the astronaut with a comfortable and reliable way to control the rover and associated systems. The governing concept for the control input systems is a "Drive-by-Wire" design. This concept is utilized to allow flexibility in the design, thereby supporting multiple methods of rover control. This will provide enhanced reliability and usability. Astronaut controlled rover missions can be separated into three command environments: spacesuit-based control, manual operations from the rover, and teleoperations from base.

Voice Command System

The astronaut will utilize spacesuit-based control when the rover is acting as a field assistant. In this mode, the astronaut is assumed to be primarily involved in surveying the surface for geological purposes. The astronaut will be mobile and involved in tasks that require the use of both hands as he surveys different areas. Voice activation technology will be utilized. The majority of control inputs to the rover will consist of pre-defined tasks such as moving to the next marked area or conducting sampling and field documentation operations. An automated pilot feature would also be appropriate in this scenario to minimize required control input.

Voice activation systems are non-intrusive control input systems. This prevents interruption of tasks that require the use of the hands or visual attention. This input technology is very suitable for the astronaut who requires assistance from the rover while he is mobile on the field performing geological research. The system will efficiently recognize and execute voice commands spoken by the astronaut. A voice identification system is more appropriate than voice verification system, since there exists no concern for strict verification of the user's identity to control access. Voice verification would also introduce problems of false rejection of commands because it did not match the specific range for parameters such as pitch and frequency of speech stored in the user's profile. Voice identification systems only attempt to identify the spoken command and provide a best match to stored command profiles [7].

Voice activation systems may be either text-dependent or text-independent. Text-independent systems will recognize unexpected words and then use complicated algorithms to determine their meaning. These systems require significantly more training time and have lower word recognition rates than text-dependent systems. Since unexpected commands are unlikely, it is more robust to implement text-dependent command profiles. These are lists of commands that the rover is programmed to recognize and the user trained to use. In addition to text-dependency, voice activation systems can be designed with whole-word models, where a match must be made for the entire word, or sub-word models, where the system can recognize part of the word and interpret the remainder of the command. In this design, whole-word models are used to minimize false interpretation [8]. Errors can be further reduced by selecting command parameters with minimal similarities and by creating robust command profiles through system and user training [9]. The system requires a microphone for input and will utilize the one located inside the helmet for audio communication. This is the preferred location as several studies have shown that close-talking microphones are optimal for speech recognition. A second microphone will be used for noise cancellation that will reduce error due to noise interference. The expected word recognition rate for this system is 99% based on current technology [10].

The astronaut will address commands to be executed either by the rover computer or at a portable computer integrated in the Primary Life Support System (PLSS). Commands addressed to the rover include all steering commands, lights, cameras, robotic arms and rover computer system. Commands addressed to the spacesuit portable computer include control of display information, PLSS status, rover assignment, etc. The command structure will be "Receiving Computer + Operation + Directive-1 + Directive-2."

Examples to Rover
"Rover-1...Easy…Right…270"
or
"Rover-1…Stop"

Examples to Spacesuit-Based Computer
"Computer…Display…Nav"
or
"Computer…Helmet…Light…Off"

Manual Command System

At times, the astronaut may also desire fine control of the rover. Redundancy in case of problems with the voice control system is also desirable. This can be achieved manually from onboard the rover or from base. In these situations, the astronaut can dedicate the use of his hands to controlling the rover. Hence, the integration of a manual hand controller or control pad, both very well developed and reliable control input technologies.

The spacesuit control pad serves as a backup to voice control when the astronaut is away from the rover. The arm pad also permits fine control of the rover and robotic arms when the astronaut is dismounted, as extensive fine control is tedious via voice input. The layout of the input buttons and switches will be designed to meet General Design Requirements Document (GDRD) specifications. The arm pad provides controls operation of:

- Lights and Cameras (On/Off/Positioning)
- Robotic arms (On/Off/Positioning)
- Stop all rover motion (Safety)
- Helmet-mounted display and arm liquid crystal display (LCD) configurations
- Communications/"SOS" message

A hand controller is located on the right armrest of the rover. It is similar in design to that used to control the lunar rover, utilizing a four-direction input device shown in Figure 7. The astronaut will push the hand controller forward to accelerate; pull the hand-controller towards his body to brake; or rotate hand controller left or right to turn in those directions. The center position is an idle mode. Using a switch on the rover control panel, the astronaut will select either the forward or reverse direction. The hand controller is the primary control input while the astronaut is onboard the rover. It provides quick response to steering commands and is thus preferable for navigating around obstacles. For long traverses an autopilot function will be used to minimize required astronaut intervention.

Figure 7: Hand controller [11]

A control panel is located on the left armrest of the rover to compliment the hand controller. The control panel acts as a backup to voice commanding and provides speed regulation and emergency stop functions. The rover control panel layout will also be designed to meet GDRD requirements. The functions available from the control panel include the same operations as are available from the arm pad, plus a display of speed regulation and rover direction.

Rover Display System

The rover display system tries to complement an astronaut conducting surface exploration. In this role, the astronaut will benefit substantially from having a large quantity of information available while both on and off the rover. However, the information must not obstruct the view of the environment. With these requirements in mind, a display system incorporated into the helmet of the astronaut's space suit has been selected as the most suitable solution for the primary display. An LCD integrated within the spacesuit arm will back up the above display system.

The best design for the helmet mounted display would have a high resolution system visible in a wide range of lighting conditions that has a data rate capable of supporting video broadcast. A traditional projection style of display is selected to meet the rover display requirements. Military rotorcraft pilots currently use these systems to display information during flight. These designs could be adapted to meet the requirements of a surface exploration mission. The helmet-mounted display will consist of a miniaturized projection device mounted in the spacesuit helmet that will display information on a transparent screen mounted inside the spacesuit helmet. This internal screen design is selected to improve resolution of the display through optimal material selection with regards to optical properties and strength requirements. In addition, the display system will utilize the PLSS computer to control image display and communication with the rover's systems. Voice commands allow the astronaut to select which information is displayed. If the voice command system malfunctions, the control pad in the arm of the spacesuit will allow the astronaut to make these selections manually.

The rover periodically broadcasts its status and navigation information to the astronaut's space suit. This information allows control of the rover via the voice activated command system or the spacesuit arm integrated control pad. Voice activated commands are displayed to permit verification of the command by the astronaut prior to execution. Navigation information and rover status will enhance astronaut situational awareness while conducting dismounted field operations. In addition, PLSS status can be monitored via the helmet-mounted display.

The astronaut is able to view images obtained by cameras mounted on the rover. This includes both telescopic and microscopic images obtained in support of the scientific mission. This feature enhances the astronaut's ability to conduct geological exploration. The astronaut also would have access to other information, including checklists, procedures and reference information that would enhance the performance of field exploration.

The spacesuit arm will contain an integrated LCD device that is able to display alphanumeric information. This device will serve as a backup to the helmet-mounted display during periods when the astronaut is not aboard the rover. While the astronaut is riding the rover, a rover mounted LCD will serve the same function. This technology is very rugged and requires minimal electrical power. While these displays do not have the same functionality as the helmet-mounted display, the mission can still be performed in the event of a malfunction.

Navigation and Obstacle Avoidance

The rover must be capable of two navigational modes. The first mode is "human in the loop," which includes the astronaut riding on the rover, the rover following the astronaut, and either local or remote teleoperation. The second is an autonomous mode, in which the rover will drive itself to a location (probably previously marked by an astronaut as being of interest), perform some work there, and then return to base. These two modes call for different navigational approaches.

When a human is controlling the rover, either directly or by setting a path for it to follow, he is already performing the primary navigation for the vehicle. There is no strong need for computationally complex systems to duplicate the astronaut's excellent obstacle avoidance, navigation, and path planning abilities. There is, however, the chance that the astronaut may overestimate the rover's abilities and try to drive it in dangerous ways. For instance, the astronaut may attempt to drive up an incline that would capsize the rover. To avoid damage, simple reactive sensors like tilt switches and bump sensors can be used to alert the astronaut that there is a problem. Several sets of such small, compact sensors can be used to specify risky or "yellow" rover configurations and dangerous or "red" configurations. In a "yellow" situation, the rover could function safely, nearing its stability limits. A "red" situation represents reaching these limits, within a specified safety margin. When a sensor goes to "red," the rover will stop and alert the astronaut, who must carefully remove the rover from that situation.

When the rover is operating autonomously, it may need to travel more slowly. It will need to process its stereo video data of the area to determine obstacles, which is computationally expensive. Stereovision can be used to determine the height and range of obstacles in the area. Once the obstacles are identified, artificial potential field techniques can be used to avoid them. Artificial potential field techniques identify obstacles and assign "potential fields" which "repel" the mobile robot. The closer the robot gets to the field, the stronger the "repulsive force" becomes. This pushes the robot away from dangers and towards a safer path. The autonomous path planner will use this information to determine the path. It will interface with the other rover systems as if it were a human user. Its actuation commands will be packaged like those sent by the astronaut. This way, any predicted user, human or not, can use the same software to actuate the rover's controls.

Passive Astronaut Following

The astronaut may wish to explore a worksite on foot, but keep the rover nearby to hold tools and accept samples. In this case, it is desirable to have the rover semi-autonomously follow the astronaut. The astronaut is constrained to pick a path the rover can follow in this case. A passive color vision-based astronaut tracking system is selected since it utilizes the cameras mounted onboard the rover for the autonomous mode. Moreover, there are no transceivers that could fail. Although color-based systems are sensitive to changes in lighting conditions, this can be mitigated to some extent by the methods used to train the tracking software. Current research intends to quantify how robust the tracking system is to differences in lighting.

In the proposed system, the astronaut will wear a colored target. The vision software can be trained to recognize this color and extract "blobs" of it from a frame of video. This "blob tracking" is a much faster process than other vision techniques such as object recognition. The size and orientation of the color blob translates to the range, heading, and orientation of the astronaut. If the target is a circle, for instance, a nearby, front-facing astronaut is identified by a large colored circle. The area of the circle corresponds to the distance from the rover to the astronaut. If the astronaut is further away and turned slightly, the target is smaller and more elliptical [12]. The rover can, in this manner, track the astronaut and record his path relative to the rover. This can be stored in some short-term memory, allowing the rover to follow the astronaut's footsteps

Communications

The communications subsystem is intended to provide reliable communications between the astronaut, the rover, and the base during planetary explorations. Two different communication links are required to transmit video, voice, and data in these missions. The first would accommodate local communications, which is defined as astronaut-to-astronaut, astronaut to rover, and astronaut to base when astronaut is less then 10 km away from the base. For this link, the driving requirements are the bandwidth and data rate, rather than the distance between receiver and transmitter. The second is for distant communications when the rover is more than 10 km away from base, or in the case of an obstacle higher than the 3 m high antenna on the rover. Video, voice, and data will be compressed in the same data stream to enhance efficiency and minimize electromagnetic interference [13].

Communication Links

Astronaut to Astronaut

Primarily, this link will allow voice interactions between the astronauts during the conduct of EVA. Astronauts will be able to communicate with each other without being in the vicinity of a rover. It will function over short distances. This link will be supported by transceiver and antenna contained within the astronaut's spacesuit.

Astronaut to Rover

This link supports video, voice, and data exchange between the astronaut and the rover over short distances. The astronaut will send voice commands to control rover operations and functions. Mission video is transmitted to the rover from the spacesuit helmet-mounted camera. In addition, the astronaut's physiological information will be transmitted to the rover. The rover status and navigation information is transmitted to the astronaut to enable rover control when the astronaut is dismounted. Video from rover-mounted cameras is also sent to the astronaut to support geological exploration.

Astronauts to Base

This link utilizes either the local or distant communication antennas depending upon distance from base. If far from base, the rover functions as a relay station between the astronaut and base by utilizing the distant antenna to retransmit astronaut communication. In addition, the rover will intercept voice communications between the astronauts for retransmission to the base, if desired.

Rover to Base

This link allows for transmission of video and data from the rover to the base in support of teleoperations, autonomous missions, and EVAs. The local or distant antennas will be utilized depending upon distance from base. Rover and astronaut status is periodically transmitted to base during the EVA to allow for monitoring while minimizing power consumption. Furthermore, all information can be transmitted continuously depending upon the mission profile.

Antenna

As mentioned above, the rover will have one antenna for local communications and a second for distant communications. The data rate of 8 megabits per second and the bandwidth of 12 megahertz are a compromise between the amount of data we want to transfer (video, voice, and data) and the power required to transmit it with an omni-directional antenna [14]. The main advantage of this type of antenna is that it does not need to continuously track the astronaut for communication, but it requires greater power, as it is a low-gain antenna. Quadrature phase shift keying modulation is used to minimize bandwidth, and thus power requirements [14, 15, 16]. For distant communications, a parabolic antenna was chosen to minimize the power requirements for transmission over long distances. When line of sight is compromised, this antenna overcomes the problem by rotating the dish to communicate with a satellite assumed to be orbiting about the planet.

Human Interfaces

The main objective of the human interface aspect of the rover design is to establish astronaut access to the rover for data collection and seating, and to improve the comfort for the astronaut while riding onboard. In the design, minimization of fatigue, the need for special training, and simplicity of design, use and maintenance were also emphasized. The study focused on a 25th to 75th percentile American male in a spacesuit.

Vehicle Access

The astronaut has access to the vehicle in four locations. Ingress to and egress from the vehicle is at the front of the rover, as the wheels restrict the area directly to the right or left of the seat. Access to tools and workspace is at mid-body, between the wheels, where an 80 cm envelope allows ample room for an astronaut wearing a spacesuit. The robotic arms and sample tray, which can carry up to 100 kg of samples, are located at the back of the vehicle. The astronaut should have minimal contact with the robotic arms, but can access the arms and vehicle from the rear if necessary.

In the case that one rover breaks, the astronaut riding that rover would stand in the workspace area located in the mid-body section of first rover and hold onto the overhead structure. If the astronaut were to be incapacitated, he/she would be put in his/her own rover, which would follow the functional rover back to base.

Storage Workspace

The storage bins located between the wheels provide space for the astronaut to store manually collected samples as well as access the data collection computer and microscope. The upper surfaces of the bins provide a workspace for cataloging samples and an interim location for samples and tools while working. The work envelope for the suited astronaut allows him to reach to the center of the vehicle, where the portable toolbox is located, making the entire workspace accessible.

Seat Design

The astronaut is seated at the front of the rover such that the footplate is forward of the main rover body, but aft of the front tires. This position provides the best visibility as well as providing a counterweight at the front of the vehicle for the weight of the robotic arm system at the rear. The seat structure conforms to the spacesuit and PLSS to provide lateral stability.

The relative positions and angles of the seat, footplate, and back were chosen based on the experimental findings of a Johnson Space Center test [17]. Four different suits were tested for comfort and ingress/egress mobility into a rover seat mock-up. Adjustments were made in the seat height, the distance between the footplate and the front of the seat, the angle of the seat back, and the relative position of the t-handle controller. Tests were conducted in 1-g and in Martian gravity simulation aboard the KC-135 aircraft. The results of this study demonstrate that there is a preferred range of seat settings that corresponds to all suits. This study also revealed two key elements of the astronaut's sense of security and comfort, solid contact at the footplate and height. The distance between the footplate and the front of the seat must be short enough that the astronaut can provide a stabilizing force at his feet, yet large enough for ample space to stand in front of the seat. The resulting preferred range is 36 to 46 cm. The BURRO is designed with a 36 cm distance. In regards to seat height, lower seat heights from 32 to 47 cm were more conducive to easy ingress and egress as well as providing a feeling of greater security. The BURRO seat height is 35 cm from the deck of the footplate.

Good visibility is dependent on a third variable, seat back angle. Test results demonstrated a range in preferred angles from 60º to 110º measured from the horizontal. BURRO is shown to have an 80º seat back, but is adjustable within the stated range. Due to the seat height and orientation of the footplate relative to the seat, a pivot is incorporated such that the footplate may be rotated downward to provide a step. Once on the step, the astronaut backs up and is aided into the seat by rotating the footplate back up to the riding position.

Restraint System

The astronaut restraint system is designed for both safety and comfort. A pivoting shoulder harness is incorporated instead of a traditional lap belt. Apollo astronauts were dissatisfied with the lack of lateral restraint provided from the lap belt, as a shoulder harness will help to limit lateral slip. In addition, the lap portion of the restraint may be used to incorporate control interfaces and vehicle status displays. Pivot joints must be protected from dust to avoid degradation of the mechanisms.

Science Payload and Tools

The science payload is comprised of geological sampling tool, which are shown in Figure 8, cameras, and the robotic arms. The geological tools include:

- Wrench
- Rock hammer
- Scoop
- Magnifying Glass
- Power Drill
- Robotic End-Effectors (scoop, gripper)
- Flag markers

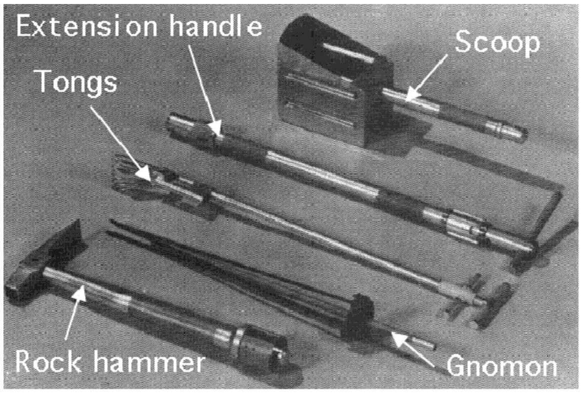

Figure 8: Hand tools available to the astronauts [18]

The tools selected are easy to use and require little training or workload. They are located on shelves directly behind the astronaut's seat and in the portable toolbox. This toolbox can be removed from the deck of the rover so that the astronaut can conduct science activities away from the rover and return samples easily using a dedicated sample bag.

The rover also carries flags to mark sites of scientific interest or danger to the astronaut. The flags have a green background that contrasts with the Martian soil and have a shape code to indicate whether samples have to be collected (circle in the lower right), pictures taken (triangle in the upper left), both, or just warning of a hazardous area (large X), as shown in Figure 9.

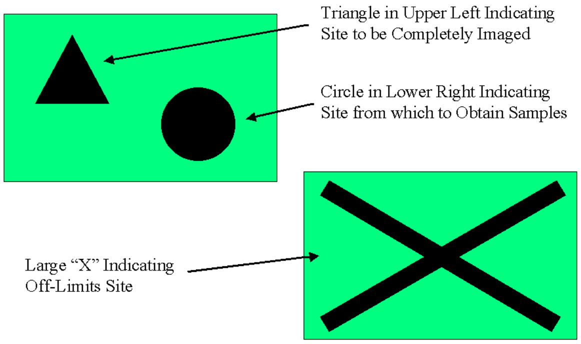

Figure 9: Flags marking sites

Surveying of the landscape is done with the panospheric camera, providing global knowledge of the Martian environment and vehicle position with respect to the surrounding area. However, during rover teleoperation, the operator utilizes the pan/tilt stereo camera to provide a close-up view of the terrain through which he is navigating.

Detailed science imaging is conducted using the infrared camera with 3 to 5 micrometer wavelengths, providing information on thermal activity. This camera also provides a wider spectrum of observations, enhancing the inspection of the landscape [19]. The telescoping zoom lens has better resolution than the stereo camera and provides detailed images of samples and the surrounding area before they are collected. The entire vision system is mounted on the overhead structure, which can be seen in the picture of BURRO in Figure 1.

The astronaut uses the microscope to examine rocks and soil that have been sampled manually. The zoom magnification capability is greater than that of a hand lens and provides a stable base upon which to observe objects and take measurements. Images are transmitted through a video link to the data collection computer and are projected on the computer screen. The data collection computer accepts video inputs from the microscope, telescoping zoom, infrared camera, and the robotic arm-mounted camera. The data collection computer and microscope are stored in the bins located at the rover mid-body, between the fore and aft wheels.

Conclusions

As detailed in this paper, BURRO will greatly enhance the efficiency of astronaut exploration and experimentation on Mars. Utilization of the rover mitigates astronaut fatigue since it carries scientific instruments and samples and performs dexterous tasks with its robotic arms, freeing the astronaut to walk longer and explore further. By employing a number of imaging tools, the rover allows more exact knowledge of in situ samples and mapping of the Martian terrain. BURRO increases the area about which astronauts can safely roam by providing an amplification of the communications relay between the explorer and base and ensuring the transport of an incapacitated astronaut. When NASA plans its first manned exploration of Mars, BURRO would significantly increase the knowledge gained from the experience.

Future Work

A number of design elements remain to be addressed. These include a preliminary cost analysis, detailed reliability analysis, and component level design. A preliminary reliability analysis was conducted using a fault tree method. This revealed that the rover/astronaut pair concept of operations is fundamentally sound with regards to minimizing risk.

However, a detailed reliability analysis should be conducted upon completion of the component level design.

The next logical step in the design process should include the construction of a test vehicle for research operations on Earth. The rover subsystems outlined in this paper could then be implemented and analyzed. This rover testbed would validate the design concept and provide an experimental basis for future enhancements.

Acknowledgements

This work was completed as part of a graduate-level design course in the spring of 2001 taught by Dr. David Akin, Associate Professor of Aerospace Engineering and Institute for Systems Research, and Director of the Space Systems Laboratory. Members of the design team include: Yannick Penneçot and Melissa Turner, Systems Integration; Jamie Lennon, Rhiannon Peasco, and Juan Raymond-Santamaria, Electrical Systems; Jean-Pierre Chamoun, Paul Frontera, Erica Lieb, and Corinne Ségalas, Human Interfaces; and Michael Flanigan, David Hart, Nicolas Perriault, and Gregory Shoup, Structures and Mechanisms.

We would like to thank Rob Ambrose and Chris Culbert from NASA/Johnson Space Center for their invaluable input to this project.

We would also like to thank Glen Henshaw and Gardell Gefke for their comments, edits, and commiseration.

Acronyms and Symbols

°	degrees
BURRO	Basic Utility Rover for Research Operations
C	Celsius
cm	centimeter
EVA	extravehicular activity
GDRD	general design requirements document
J	joule
kg	kilogram
km	kilometer
km/h	kilometer per hour
LCD	liquid crystal display
m	meter
mm	millimeters
N	Newton
NASA	National Aeronautics and Space Administration
Nm	Newton meter
PLSS	primary life support system
rpm	rotations per minute
WBB	warm battery box
Wh	Watt hour

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