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Robotic Concepts for Operation in Barren Terrain

Final Report

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1 Introduction

We have performed a series of studies and configurations for robots that are capable of operating in rough barren terrains. The environments we are targeting are like those of the moon or other planets in the roughness and starkness of the terrains, the loose and hard materials that range from sandy slopes to boulder fields, and the extremes of temperature that are encountered in such places.

We present a mission scenario, requirements and then present and evaluate a mechanism design. Additional subsystem issues of power, communication, sensing, and computing are all addressed with respect to these requirements.

2 Mission

Barren Terrain Robots (BTR) have requirements far beyond those of traditional factory vehicles or even the laboratory tests of many mobile mechanisms. The BTR's primary mission is to survey an area for the purpose of identifying debris. This debris could be the remains of a satellite that has reentered, a crashed airplane or even enemy landmines all of which may be hazardous for humans. By identifying and locating this debris with robots, human exposure to the site is reduced, and possibly even eliminated if robots can manage the clean-up operations. The BTR can also be used to perform a high resolution, site survey to learn about the micro-structure of the area. This mission could be valuable to lunar missions that precede the larger, more complex and costly manned missions that are planned for the end of the decade.

To survey a site to determine the location of debris, a group of BTR's are deployed into the site. These robots will be deployed by a small team from a transport vehicle. The transport vehicle will act as a relay station between the rover(s) and the base station, see Section 6. Once debris has been identified, its location and the data that identified it are transmitted through a radio telemetry link to the ground vehicle where it is relayed to the base station via microwave or satellite link.

To be useful, a small number of rovers must be capable of surveying a 1 km^2 area within one day. For the purposes of this report, surveying means identifying all objects that are 1 cm or larger within the designated area.

2.1 Requirements

The BTR must meet certain requirements that are typical for rovers that operate in an unknown, unstructured environment. These include the ability to move through a variety of terrain types in various conditions, the ability to survive in the environment, the ability to complete a specified mission and the ability to process acquired data and dispatch it properly. These requirements impose the need for capable sensors and perception systems, robust mechanical configurations, mission planning and telemetry systems.

The BTR is designed to traverse unknown, unstructured terrain. Such terrain may have a wide variety of features that impede motion. Obviously, no robot can be built that can handle all conceivable terrains. The BTR will have the capability to negotiate obstacles up to 1 meter in size. With its on-board computing and sensing, it will have the capability to avoid larger obstacles by planning alternate routes to avoid them.

The BTR will also be self-sufficient and will be able to handle different weather conditions. With proper component and material selection, problems caused by moisture and heat can be minimized, simplifying the design of the robot.

To design the BTR, some preliminary metrics of required performance are required. These can be derived from the mission goal of surveying a 1 km^2 area within one day. This objective forms the basis for determining the BTR's operating speed, which in turn drives the design of the rest of the robot.

2.2 Speed vs. resolution vs. number of robots

Determining the minimum required resolution for the mission is an important step in the design phase. Once the resolution has been chosen, sensor placement and orientation can be chosen, and the time it takes the rover to survey a given area can be found. Knowledge about the size of the debris is, therefore, necessary to optimize the design of the rover.

As stated previously, the BTR must identify object as small as 1 cm. Using the Nyquist sampling theorem, this indicates a resolution of 0.5 cm per pixel. To simplify the mathematics, it is assumed that the plane of the camera imaging element is parallel to the ground. A standard camera with 512×512 pixels will cover an area of 6.5 m^2 with a resolution of 0.5 cm/pixel. Figure 2.2-1 below shows two ways that a single camera can be used to survey an area. The unshaded box shows

Figure 2.2-1 Areas seen by fixed and rotating cameras

the area that can be observed with a fixed camera. However, by rotating the camera, the two shaded boxes can also be observed. Since rotating the camera requires less time than moving, this technique can cover the same area at almost three times the speed the fixed camera. The squares shown are simplifications of the actual area seen, which is trapezoidal due to the oblique angle that the camera has with respect to the ground.

A best-case estimate of the time required to complete a given mission can be found using the following formula:

$$T_T = \frac{A_T}{A_S} \left(\frac{1}{v} + T_S \right) \frac{1}{n} \quad 2.2-1$$

where, T_T is the time required to survey an area A_T , v is the speed of the robot, A_S is the field of view (FOV) of the sensors, T_S is the time required to acquire each image and n the number of robots. This equation assumes touching, but non-overlapping FOV's. Using this equation, a trade study between resolution, mission duration and cost (number of robots) is easily evaluated.

Using the rotating camera technique and assuming $A_T = 1\text{km}^2$, $A_S = 2.5\text{m}^2$ and $T_S = 2\text{s}$, Equation 2.2-1 reduces to

$$T_T = 53,333 \left(\frac{1}{v} + 2 \right) \frac{1}{n} \quad 2.2-2$$

where v is in m/s and T_T is in sec. Plotting v versus T_T for 1,2,4, 8 and 16 robots yields the following plot, Figure 2.2-2 where T_T is given in days. Since rover speeds greater than 1 m/s are achievable,

Figure 2.2-2 Speed vs. Survey Time

this problem appears to be tractable, i.e., a small number of robots can survey the target area in a short period of time.

3 Mechanism

As previously discussed in Section 2.2, the speed requirements for the robot are quite severe, however, given the requirement to negotiate difficult terrain, we are proposing a walking robot as an appropriate solution to this problem. The particular type of robot under consideration is referred to as a walking beam.

3.1 Walking beams

The walking beam is one of the simplest walking robot designs. Figure 3.1-1 is a picture of such a robot. This particular implementation has several important distinctions:

- Inherent stability - The center of gravity remains within the polygon formed by the feet in contact with the ground at all times.
- Compact storage - The storage volume is a cylindrical volume with a diameter 1.16 L and height L.
- Body stability - Since each of the vertical axes is independently actuated, the motion of the body is decouple from the underlying terrain. This provides great benefit to the planning and navigation problems.
- Terrain handling ability - Beam walkers are frequently criticized for poor terrain handling capabilities. This particular implementation, however, can negotiate 20°+ slopes at full stride.

The next several sections will be a discussion of designing a particular instantiation of this robot to suit a particular mission. Section 3.1.1 provides a general introduction to the problem, including those key component technologies required and assumptions used. Equation 3.1.2 shows

FIGURE 3.1-1. WALKING BEAM ROBOT

how the robot is deployed. Section 3.1.3 describes how to size the structural elements of the robot. Section 3.1.4 shows the walking sequence for this robot, the power required to walk at a fixed speed and a plot of power versus speed. Stability, power consumption and ground clearance are mutually antagonistic goals, and resolving them is discussed in Section 3.1.5. Section 3.1.7 provides the rest of the design, including a chassis design, component housing, thermal control, etc.

3.1.1 Technologies used and assumptions made

To achieve a viable design, state of the art technologies have been used in a number of areas, including, titanium construction, batteries and computing hardware. This robot is intended for use on the Earth's surface.

3.1.2 Storage and deployment

For a robot of this design to move, the deployed leg, see Figure 3.1-1, must extend beyond the body. The further it extends, the greater the stroke at the expense of mass, power and slope climbing ability. Regardless of its length, the deployed leg must be kept "folded" for compact storage. The technique proposed is a "tube within a tube" technique, where the deployed leg is collapsed during storage and is deployed by simply pulling the leg into position, Figure 3.1-2, where it is held by a simple spring latch mechanism, similar to those found on vacuum cleaners or automobile safety belts.

3.1.3 Member sizing

To size the legs of the robot, a most probable cause of failure must first be assumed. Since titanium is being used, failure due to axial compression exceeding the tensile strength of the material can be easily discarded. Also, since the robot is designed to walk with the legs remaining vertical, the bending loads on the legs should be quite small, so this failure mode is discarded. The legs are,

however, long, slender rods, so the most likely failure mode is probably due to buckling. The equation for column buckling is

$$P_{cr} = \frac{n\pi^2 EI}{l^2} \quad 3.1-1$$

where P_{cr} is the critical load, n is a constant that depends on the conditions at the ends of the column, E is the modulus of elasticity for the material used, I is the moment of inertia of the beam and l is the length of the beam. Since each leg of the robot is to be capable of supporting the entire weight of the robot, and since the size of the robot is known, the only unknown in Equation 3.1-1 is I . Rewriting this equation yields

$$I = \frac{Nmg l^2}{n\pi^2 E} \quad 3.1-2$$

where m is the mass of the robot, g is the acceleration of gravity and N is a factor of safety. Assuming fixed-free end condition ($n=1$) and a factor of safety of 2, the required moment of inertia is found to be

$$I = 3.61 \times 10^{-10} \text{ m}^4. \quad 3.1-3$$

The lightest, available tube that can meet this requirement is a 14 mm diameter with 0.5 mm thick wall, with a linear density of 0.094 kg/m. The mass of a set of 3 legs is 0.282 kg.

To size the y-frame, it is not the failure of the frame that is a primary concern, but rather its rigidity. To size this frame, the maximum deflection of the frame is expressed as a fraction of the total leg height. For purposes of this analysis, the frame can be treated as a simply supported beam with the load occurring off center. The formula for the maximum deflection is

$$y = \frac{A^2 B^2 F}{3EI l}, \quad 3.1-4$$

where F is the load, A is the position of the load along the beam and B is the length of the beam less A . Again, the only unknown is the moment of inertia, so Equation 3.1-4 is rewritten as

$$I = \frac{NA^2B^2mg}{3YEl^2}, \quad 3.1-5$$

where Y is the fraction of l of permissible deflection. Values for A and B are obtained from Figure 3.1-2., Y is chosen to be 0.01 and the safety factor is 2. Solving Equation 3.1-5 for I yields

$$I = 1.81 \times 10^{-8} \text{ m}^4. \quad 3.1-6$$

The lightest, available tube that can meet this requirement is a 42 mm with a 0.7 mm thick wall, with a linear density of 0.402 kg/m. The mass of the frame is 1.023 kg.

The masses given for the legs and frame do not include motors, gear rack, structural support elements, etc. However, these values will be used to provide a first estimate of the power requirements, see Section 3.1.4. Once the power requirements have been determined, the masses of these elements can be calculated, then final power figures can be obtained.

3.1.4 Power vs. speed

The issue of determining the power required to move at a given speed is complicated by the interactions of the robot with the underlying terrain. To provide a clear explanation of the trade-off between power and speed, Section 3.1.4.1 provides the basic tools necessary for this analysis, Section 3.1.4.2 performs the analysis neglecting soil work and Section 3.1.4.3 performs the same analysis, but soil work is included.

3.1.4.1 Kinematic profiles and power equations

A complete cycle of motion for the walking beam is comprised of six distinct stages, Figure 3.1-3. For each transition between stages, here after referred to as phases, where phase 1 is the transition between stage 1 and stage 2, a kinematic profile can be defined. The profile chosen for this robot is a trapezoidal velocity profile, Figure 3.1-4.

Figure 3.1-4. Kinematic Profile, Trapezoidal Velocity

For each phase, the distance x to be traversed is known and the traverse time T can be specified, see Sections 3.1.4.2 and 3.1.4.3, so only the acceleration time, t_{acc} , needs to be determined.

Figure 3.1-3. Walking Sequence

To find an optimal value for t_{acc} an equation for the power required, P , is derived, then the following equation is solved for t_{acc}

$$\frac{\partial P}{\partial t_{acc}} = 0. \quad 3.1-7$$

This equations can not be solved for t_{acc} in a closed form. Instead of using this equation, the approach used will be to find the minimum power required due to inertial effects and add the power required from other sources.

The governing equations to determine the power needed to accelerate a body are

$$P = Fv \quad F = ma \quad 3.1-8$$

From Figure 3.1-4 we can write the following equation for the position

$$x = at_{acc}^2 + v(T - 2t_{acc}). \quad 3.1-9$$

From Figure 3.1-4 and Equation 3.1-8, it is clear that the maximum power occurs at $t = t_{acc}$. At this time, the velocity is given by

$$v = at_{acc}, \quad 3.1-10$$

so substituting Equations 3.1-9 and 3.1-10 into Equation 3.1-8 yields

$$P = mav = ma^2 t_{acc} = m \left(\frac{x^2}{t_{acc} (T - t_{acc})^2} \right). \quad 3.1-11$$

Differentiating Equation 3.1-11, setting the resultant equal to zero and solving for t_{acc} yields $t_{acc} = T/3$. Substituting this into Equation 3.1-11 yields

$$P_{inertia,min} = \frac{27mx^2}{4T^3}. \quad 3.1-12$$

3.1.4.2 Power required - Soil work neglected

There are three primary sources of power expenditure during motion: inertial, gravitational and frictional. Inertial power losses were examined in Section 3.1.4.1. Gravitational power is given by

$$P_{grav} = mgv \quad 3.1-13$$

and frictional power losses are given by

$$P = \mu Nv \quad 3.1-14$$

where N is the normal force. There are other possible power requirements, such as aerodynamic drag, but they will be ignored. It is also assumed that non-regenerative motors are used, therefore power generated by gravity, when the robot descends, will be ignored.

Table 3.1-1 lists the need for including gravitational power, the mass being moved in each phase and how far it moves in each of the phases. During phases 1, 3, 5 and 6 the motion is in the direction of gravity, therefore the normal force, required for friction, is not defined. To account for the frictional power losses, however, a value of 10% of the weight of the moving element will be used in these phases. (Note that phases 1 and 4, and 3 and 6, are identical.)

	Gravity	Mass	Displacement
Phase 1	x	m_l	0.25 L
Phase 2		m_f	0.81 L
Phase 3		m_l	0.25 L
Phase 4	x	m_l	0.25 L
Phase 5		m_b	0.81 L
Phase 6		m_l	0.25 L

Table 3.1-1 Phase Power Parameters

The maximum power expended in each phase is now written as

$$P_i = \frac{27m_i x_i^2}{4T_i^3} + \frac{3m_i g x_i}{2T_i} + \frac{3N_i \mu m_i g x_i}{2T_i} \quad 3.1-15$$

where N is the fraction of the mass of the moving element used to determine the frictional force and i is a phase index.

To minimize the power expended, the length of time spent in each of the phases should be calculated such that the power expended in each phase is a constant. This time is found from the solution of the following set of five, non-linear equations:

$$\frac{a_{i1}}{T_i^3} + \frac{a_{i2}}{T_i} - P = 0 \quad , \quad i = 1, 2, 3, 4 \quad 3.1-16$$

$$2T_1 + T_2 + 2T_3 + T_4 = T$$

where T is the total cycle time. Figure 3.1-5 is a plot of the power required for cycle times ranging from 1 s to 60 s. This plot does not properly represent a real system, because as the power needed

Figure 3.1-5. Power vs. Speed

to move increases, heat dissipation and other, unaccounted for, non-linear affect will begin to have a pronounced affect on the system. However, if the range of acceptable speeds is constrained to be less than 0.3 m/s (1.1 km/h), the results of the calculations should be fairly accurate.

The analysis thus far has not considered lifting the body, the most power intensive motion possible. By limiting the motors to produce an output power as indicated by Figure 3.1-5, the speed of a body lift is quite low. For example, to lift the body 0.25 L (0.25 m) with 10 W of power (which corresponds to a speed of 0.32 m/s), requires 7.3 s, as compared to times without the body lift of 0.23 s, 0.85 s, 0.23 s and 0.322 s for phases 1, 2, 3, and 5 respectively. Although 7.3 s is not an inordinate amount of time, were body lifts required on a regular basis, the speed of the robot would be greatly diminished. For further discussion, see Section 3.1.6.

3.1.4.3 Power required - Soil work included

Modelling foot-terrain interactions is a complex task. For the purposes of this report, a simplified model will be acceptable so that in impact of this interaction of power consumption can be determined. The model used will be that of a simple spring, the force applied is proportional to the distance it is compressed. However, unlike a simple spring, this model will not return the energy used to compress it. It is also assumed that the contact with the terrain occurs during the last $T/3$ seconds of phases 3 and 6. This model is only a course approximation, for as the robot leg bears down on the terrain, not only will the terrain sink, but the robot will rise up slightly.

To determine the maximum power used for soil work, equations for the displacement and velocities during for the period $T/2 < t < T$ are derived from Figure 3.1-4. Power used in compressing a spring is given by

$$P = kxv \quad 3.1-17$$

where k is the spring constant of the terrain. Solving

$$\frac{\partial P}{\partial t} = 0 \quad 3.1-18$$

for t , then finding the maximum power yields

$$P = \frac{kX^2}{4\sqrt{3}T} \quad 3.1-19$$

This additional term is used in Equation 3.1-16 for phases 3 and 6. A plot of the results appears in

Figure 3.1-6. Power vs. Speed - Soil Work

Figure 3.1-5. Although this figure appears to be quite similar to Figure 3.1-5, the amount of power needed has increased. In addition, the cycle times for the phases were dramatically altered. Some examples of how the soil work impacts the power profile:

- Speed 0.32 m/s (1.2 km/h): no soil work, 10 W, with soil work, 21 W
- Speed 0.027 m/s (0.1 km/h): no soil work, 0.3 W, with soil work 0.9 W

3.1.5 Mechanical design detailing

This section will detail some of the mechanical elements of the system, including the motors, Section 3.1.5.1, the gearing, Section 3.1.5.2 and the linear bearings, Section 3.1.5.3. Section 3.1.5.4 shows some of the design details.

3.1.5.1 Motors

To achieve the highest motor output power to mass ratio, brushed DC servo motors are chosen. Although brushless motors have a higher power to mass ratio, when the mass of the commutation electronics are included, the brushed motors' superior power to mass ratio becomes apparent. The motors selected for this application are manufactured by Montevideo Technology, Inc., model number DC-08001. This motor has a diameter of 0.75 in, a length of 1.37 in, a mass of 42 gr and

can supply up to 20 W of output power. These motors are designed for use in aerospace applications.

3.1.5.2 Gearing

There are three gearing applications for this robot, motor output gearing to reduce the speed of the motor, rack-and-pinion gearing for the linear drive elements and a segment gear for turning.

Motor output gear

Selecting a cycle time determines the required gearing ratios. Knowing the power output determines the size of the speed reducer. For an overall speed of 0.32 m/s (1.2 km/h), the following joint speeds and torques (assuming a 1 cm radius pinion gear) are required (though not necessarily in the same phase):

- vertical leg axis: 165 rad/s, 2.5 Nm
- horizontal body/frame axis: 143 rad/s, 0.4 Nm
- rotational axis: 19 rad/s, 0.8 Nm

There are no gear boxes that can provide this range of values for the linear axes. Specifically, to get 2.5 Nm from the specified motors, a gear reduction of 250:1 is required, however, the maximum possible speed is then only 3.1 rad/s. This difficulty exists because the horizontal and vertical axes have two different motion profiles: high torque, low speed and low torque, high speed. One solution is to add a clutch that bypasses the gear box for high speed motion, and engages it for high torque motion. A combined gearbox/clutch system can be built to satisfy the requirements with a mass on the order of 0.25 kg. A drawback to this solution is the additional mass required for the clutch. Another solution would be to reduce the speed of the system. Using the 250:1 gear ratio, the speed of the robot is decreased to less than 0.01 km/h, which is quite unacceptable.

Rack-and-pinion gear

The rack and pinion must be sized to withstand the power and applied load. Factors taken into consideration for the design of a gear train include fracture due to excessive bending loads, fatigue failure due to repeated loading, surface abrasion due to the contact pressure and thermal loading due to the sliding contact at the interface. Gear design is a complex procedure and an analysis will not be performed. However, based on experience, the width of the gears will probably be 5 mm. The mass of such a rack will be about 0.1 kg.

Segment gear

The design of the segment gear requires the same considerations as the design of the rack, and these calculations will not be performed. Again, based on experience, a gear with a width of 5 mm will suffice. The mass of such a gear, assuming 90° of rotation and a 10:1 ratio, is approximately 0.1 kg.

3.1.5.3 Linear bearings

Traditional linear bearings “suffer” from two drawbacks: they require a hardened steel surface to roll on and they are only available in closed and open forms. In addition, they must remain fairly free of contaminants and must be lubricated. To avoid all of these problems, solid linear bearings, with Frelon, a compound of Teflon®, used as the anti-friction element is used. A standard line of these products is available from Pacific Bearings Co., but for this application a custom design will be used. This is done to reduce mass, although it will increase the cost.

A custom design is being used for the following reason. Consider the system shown in Figure 3.1-7. Since the bearing does not provide a means to prevent rotation of the tube, a torque applied to the tube will cause a transverse load to be applied to the motor shaft. There are at least two ways to prevent this: Add extra bearings to the motor shaft so that it can support the lateral load or design a system with two tubes, so that it becomes impossible to twist the tubes. Both of these methods have the disadvantage of requiring extra mass.

Figure 3.1-7. Lateral Force Applied to Motor - Standard Open Bearing Design

By using a custom linear bearing, the cut-out can be made into a bearing surface, as seen in

Figure 3.1-8. Lateral Force Applied to Motor - Custom Bearing Design

Figure 3.1-7. With this design, the tube is restricted from twisting by the cut-outs in the bearing, which are also covered with the Frelon material for a low friction contact. In addition, by designing a custom housing for the bearing material, further weight savings can be achieved.

3.1.5.4 Detail design and drawings

A full, detailed set of drawing for the robot are not presented in this section. Rather, drawings of the three types of actuators are presented to show how this design might be actualized. The overriding concern with this machine is minimizing locomotion mass so that payload mass can be maximized.

Vertical actuator

The vertical actuator is shown in Figure 3.1-9. The tabs on the mounting plate are affixed to either the y-frame or the body. The plate, shown in pink, has a mass of about 0.1 kg and comprises the leg mounting brackets, the leg bearings and the motor mount.

Horizontal and rotary actuator

The horizontal and rotary actuators are shown in Figure 3.1-10. The shaft shown in pink the connection point to the body. This shaft mates with a bearing that allows the y-frame and the body to rotate. The rotation is driven by the “pie” gear and the motor. The linear motion is similar to that of the vertical actuator. The mass of the mounting plate, which comprises the shaft, the bearings and the motor mount is 0.5 kg. The total mass used by the mechanism is approximately 6 kg, leaving 14 kg for the rest of the robot.

Figure 3.1-9. Vertical Actuator Assembly

3.1.6 Power vs. stability/ground-clearance

An open area of research is the trade-off between power, stability and ground clearance. For maximum stability, the body of the robot should be kept as close to the ground as possible. For minimum power consumption, the body of the robot should be kept as high as possible, thereby guaranteeing that a body lift maneuver need never be done. The optimal body position is between the two extremes, and is probably a function of the distribution of the obstacles to be encountered and the general roughness of the terrain.

3.1.7 Chassis, component housing, thermal control

The design of the chassis is particularly challenging because of the wide variety of instruments that must be accommodated. The chassis will be based on a framework of small diameter, titanium tubing. These tubes will have flats and flanges welded on to accept bolts for equipment. To protect the equipment, the framework will be covered with space-type solar reflective material. Although this will not provide the same type of protection that a rigid panel would, it is significantly lighter. Furthermore, since the use of a large number of robots is expected, the loss of any single robot will not kill the mission.

One of the biggest challenges will be to keep the robot cool. Because of limited power and mass, the amount of heat that can be drawn off with active cooling systems is severely limited. It is necessary that the robot be designed in such a manner that the amount of solar radiation that falls on the chassis is minimized. This can be accomplished in part with an "umbrella" of solar panels that moves so as to block the sun.

Figure 3.1-10. Horizontal and Rotary Actuators Assembly

3.2 Subsystems

The BTR's primary subsystems are power, computing, sensing and communications, each of which are below. The scientific equipment is discussed separately in Section 5.1.

3.2.1 Power

The configuration and design of the power generation and storage systems are driven by a number of issues, including:

- vehicle configuration
- available mass and area
- radiation environment
- average and peak power requirements
- operating temperatures
- shadowing and illumination
- mission life
- cost
- technological risk

Looking at Figure 2.2-2, it might seem that using primary batteries as the sole source of power is a viable solution. However, to do so would severely restrict the BTR potential capabilities. Instead, the BTR will use solar and/or wind power generation and will start the mission with fully charge secondary batteries. With the given operating scenario, the BTR's total power consumption is probably less than 50 W. Assuming advanced battery technologies (rechargeable silver-zinc or lithium-ion, 110 w-hr/kg), with 1 kg of the total mass used by the batteries, an average of 40 W needs to be produced (assuming a 12 hour work period).

To generate this power with solar cells, 0.5 m² of amorphous silicon solar cells are required. Using thin film technologies, the mass is ineligibile. However, solar cells do not work efficiently in poorly lighted areas and there will be a wind load imparted to the BTR.

Wind generation can provide this power also, however, it has other drawbacks. The first is that the generator is quite heavy, on the order of several kilograms. The other is the second law of thermodynamics, specifically, the power needed to overcome the wind-loading on the turbine (when moving in the direction of the wind) will be greater than the power generated by the turbine. To overcome this problem, the BTR would move, stop and unfurl the turbine blades, store energy in the batteries, then stow the turbine and keep moving. This added complexity and mass is not deemed reasonable for this mission unless other environmental consideration rule out solar power generation.

3.2.2 Computing

The BTR requires extensive computing resources due to the data processing done on-board. Although detailed computing requirements have not been estimated, based on previous system, the BTR may well require 100 MIPS and 25 MFLOPS of computing capability. Two options are currently being considered for the BTR: the first is based on the Harris developed, MIPS R3000 series processor with space qualified packaging and the second is a ruggedized commercial computer, such as a Sun Microsystems Sparc 2.

The Harris solution offers several benefits: Since it is designed to meet space qualification procedures, the computer is rugged and can survive in a radiation environment. Second, the system has built in redundancy and fault tolerance. Finally, the system is fabricated using advanced multi-die modules, which permit placing an entire system in several square centimeters with minimal power requirements. Harris has also developed multi-chip memory modules with densities exceeding tens of megabytes per cubic centimeter. The major drawback to this solution is its cost, both to purchase and to port existing operating systems and software.

The commercial processor solution is orders of magnitude less expensive than the Harris system and it has the benefit of being well understood by the software developers. However, the computer is physically quite large and consumes a fair amount of power. In addition, commercial processors are not as environmentally rugged as those designed for space application. The proper selection of the processor for this mission will depend heavily on available funding, although the commercial processor may have a great impact on the rest of the system

3.2.3 Sensing

The BTR's sensors can be broken down into two groups based on the sensor's function: those that are used primarily for vehicle navigation and health monitoring, and those used primarily for carrying out the scientific mission. Because of similar needs, several of the sensors can be categorized as belonging to either group, so they will be listed in the group that represent their primary use. The sensors primarily used for the scientific mission will be discussed in Section 5.1.

The BTR will require several different internal sensors for health monitoring and position estimation. These include contact sensors, proximity sensors, inertial navigation units (IMU) and global positioning systems (GPS).

The contact sensors and the proximity sensors will be used for safeguarding the vehicle, that is, to prevent it from bumping into items that were not detected using the vision system or object that have moved into the vehicle's path. The contact sensors may be as simple as a single-axis load cell or as elaborate as a six-axis force/torque sensor, such as the ones produced by JR³ Inc. The contact sensors will also be used to detect when a leg has been placed on the ground. This allows energy

efficient locomotion. The proximity sensors will be based on the capaciflector, a device developed at Goddard Space Flight Center and used on the CMU Erebus Explorer project.

The IMU and GPS will be used for both local navigation and debris location estimation. As the BTR traverse a path, it will need to avoid insurmountable obstacles. To do this, the vision system will be assisted by a dead reckoning system to improve accuracy. The dead reckoning system will be based on the data provided by the IMU. The GPS system will be used for global position estimation as its resolution is limited to about 35 m. When debris is located, its position will be estimated using GPS and the position of the debris with respect to the BTR, which can be determined using the imaging sensors.

3.2.4 Communications

The telemetry system design is highly dependent on the operating scenario. Using the scheme outlined in Section 6, the BTR will communicate with the base station through a relay vehicle. Since the area to be surveyed is relatively small, Section 2, the support vehicle will be relatively close to the BTR, typically less than 5 km. At this close range, an omni-directional antenna, coupled with a low power transmitter, will be appropriate.

The following is a simple link estimate that shows the viability of the concept. This estimate assumes using the Ku band with an omni-directional transmitting antenna, 1 W of transmitted power, a 0.2 m receiving antenna with 4° pointing accuracy and a data throughput rate of 10 Mbps using BPSK modulation and convolution coding with Viterbi decoding. The data rate of 10 Mbps was chosen because this is the Ethernet bandwidth, which would alleviate the need to develop additional hardware/software support. Since a viable margin is typically less than 12 dB, this link is quite robust. Commercial Ku band products with these capabilities exist and can be used for this mission.

Parameter	Value
Effective isotropic radiated power (EIRP)	-2 dB
Transmission path losses (10 km)	-134 dB
Atmospheric and misc. losses	-5 dB
Received isotropic power (RIP)	23 dB
E_b/N_0	16 dB
Coding gain	5 dB
Implementation loss	-2 dB
Margin for BER $1E^{-8}$	19 dB

Table 3.2-1 Link estimate for downlink

4 Computer architecture

For a complex piece of software to succeed, it must be organized in a coherent form. When a given form is non-changing, it is referred to as an architecture. This architecture serves as the backbone upon which a software system is constructed. A well devised architecture provides robustness, facilitates development, ensures reliability and predictability, and guarantees performance. More

specifically, when dealing with an architecture suitable for the control of robotic systems, the following capabilities are desirable:

- A robot “operating system”
- Support for performing tasks, planning and execution
- Support for reacting to changes, monitoring, concurrency and error recovery
- Conflict resolution, prioritizing goals/commands, sensor fusion and resource management.

The capabilities must be provided in face of

- A complex, dynamic, unstructured environment
- Complex tasks with competing deadlines
- Limited sensors and computational resources

Existing computer architectures can be categorized into one of three types:

- **Hierarchy** - Tasks are decomposed based on given criteria, including, behavioral, functional, temporal and spatial. Hierarchical architectures are applicable for planning, perception, error recovery strategies, etc.
- **Reactive** - The system is driven by inputs from the environment, without advanced planning. Sensors are continually monitored, decision cycles are short and there is decentralized control. The architectures work well on simple tasks.
- **Deliberative** - The task cycle is comprised of three steps: plan, monitor and replan. These architectures permit multiple focuses of attention, for example, selective monitoring, prioritizing of goal and resource management. The system are scalable and facilitate goal planning, however, there is typically no guaranteed response time and there exists possible centralized bottlenecks.

A computer architecture for a real system might comprise several of these concepts within a single software system. The overall architecture might be deliberative, certain modules would be hierarchical and the real time controller reactive. It is this type of hybrid system that is proposed.

4.1 TCA

A flexible, powerful software architecture is needed to coordinate tasks and control complex robotic systems. The Task Control Architecture (TCA) is designed specifically for robot systems that must operate autonomously for extended periods of time in uncertain, dynamic, and rich environments. In addition, the TCA is designed for robots that have multiple tasks to achieve, but limited sensors and computational resources relative to their tasks. The TCA provides a vocabulary of high-level constructs for specifying the component interactions in distributed robot systems. It also provides software utilities that implement the constructs. A system built using TCA consists of a

number of distributed modules (processes) and a task-independent central control module. The architecture for the BTR would be structured.

Figure 4.1-1 BTR Software Structure

4.2 Modules

The software is arranged in modules, each of which serves a particular function. Using the TCA, the modules are not restricted to any particular computer platform. An additional benefit of this architecture is that modules can be easily replaced as needed. For the BTR mission, the modules can be broken down into several groups based on their functionality: hardware interface, planning and mission operations.

4.2.1 Image sensing manager

The image sensor manage (ISM) serves two primary functions. Its first function is as a high level interface between the sensor control and scientific instrument interfaces and the rest of the system. Its second function is to pre-process the image data, both from the navigation and scientific sensors, and to present this information in a particular form, for example, a terrain elevation map.

All sensors require a particular interface to a compute system. This interface is typically at the hardware level, and the user of the system should not be required to work at this level. To isolate the user from this interface level, the ISM implements routines that handle all interactions with the sensors and provide the raw, unprocessed information to the user. For example, the ISM might contain a routine called `get_image`, whose function is to return, in some specified format, the image from a specified sensor. With this level of abstraction, the user needs only one routine to access any of the variety of imaging devices that may be used.

Once data from a sensor has been obtained, it must be preprocessed into a form usable by the rest of the system. For example, for range information, the planning modules are not interested in the raw sensor data, but rather a terrain map generated from this data. The ISM will provide a number of routines to convert raw data into some desired form. It is probable that a unique routine will be required for each sensor, for example, `get_terrainMap_from_scanner`.

4.2.2 Controller

For reasons similar to those listed in Section 4.2.1, the controller module acts as the interface between the planning modules, that command motions, and the actual motion control devices. By providing this interface, the user can specify desired motions and not be concerned with the implementation details of the mechanical system.

4.2.3 Base Station Manager

The base station manager (BSM) is provided so that the human operator, who is typically not collocated with the BTR, may control all aspects of the rovers activities. The BSM provides a direct interface to all routines. Typically, the operator would provide high-level commands to the system and monitor its progress. However, under certain circumstances, it may be necessary for the operator to take over control of the BTR.

4.2.4 Planners

The BTR makes use of two navigation planning modules. The higher level module is the trajectory planner, which plans the route the BTR is to travel. The lower level module is the path planner, which develops paths for avoiding local obstacles and moving to nearby requested locations.

The schism of the planning modules is well understood by use of an example. Consider getting into a car with a destination across town. The trajectory planner selects the appropriate route based on information provided by a map. Of course, the map does not provide information about other cars, potholes, etc. While driving to the destination, the path planner provides the necessary information to avoid these obstacles. Another way to consider the problem is by reaction time: the path planner requires a reaction time that is significantly faster than the trajectory planner.

4.2.5 Mission manager

The mission manager is comprised of two separate modules. The lower level portion is used to identify debris and to send the information to the base station. The higher level portion provides coordination between the trajectory planner and the mission related tasks.

4.2.6 Data manager

The data manager is required for handling the scientific data gathered. This data is first processed by the data manager to determine if the scene contains any debris. If debris is found, the data and a position tag are broadcast back to the base station.

5 Identifying debris

Determining the presence and distribution of the debris is a task that requires a very high level of quality and confidence in the detection process. Depending on the physical properties of the debris, investigation site conditions and operational scenario, various non-destructive sensing techniques could be applied to identify the debris. Once an object is tagged as being debris, the images used to make that determination and an accurate position estimate are sent to the base station.

5.1 Sensors needed

A preliminary evaluation of the proposed sensors shows that a combination of two or more sensors is required in order to identify debris. The sensors used will not require contact with the suspected debris material, thus simplifying the rover design and permitting continual rover motion since stopping to closely examine the debris is not required.

The following sensors are being considered for debris identification:

- Infrared cameras - Detects spectral signature of debris and differences between the thermal emission patterns from the soil and debris.

- Magnetic sensors - Detects changes in the earth's magnetic field caused by ferro-magnetic material.
- Metal detectors/capacitance meters - Measures changes in an electromagnetic field, produced by the transmitting coil, due to metallic objects.
- High frequency radar - Detects debris by analyzing the changes in the return signal due to the different reflexivity properties of soil and debris.
- Visual light camera - Detects object by difference in albedo and color with surroundings.

It is clear that no single, listed sensor will be able to reliably detect debris. For example, a piece of magnetite might be detected as being anomalous by a magnetometer, but the IR camera would show that it is an ordinary rock and not debris.

5.2 Sensor placement vs. resolution, etc.

The placement of the sensor on the robot impacts the size of the field of view as well as the minimum detectable object size. These mutually antagonistic quantities must be selected keeping section 1.2 in mind. The conceptually simplest scheme is to mount the cameras at the end of a 1.5 m arm that rotates about the center of the BTR in a plane parallel to the ground. By using appropriate lenses, the height above ground is not a major issue although there may be increased distortion if wide angle lenses are required. Although this is a simple scheme, it restricts the ability of the sensors to be used for other functions.

A simpler design for the sensor placement is to place them on a mast located at the center of the robot, angled down to cover some area. This scheme is not as "efficient" as the previous scheme because to get the desired resolution with the furthest pixels, the resolution of the nearer pixels will be greater than required, see below:

Figure 5.2-1 Resolution of angled cameras

This affect can be minimized by using long focal length lenses and observing points distant from the BTR. However, there is a greater probability of an object's being occluded by the intervening terrain. Further study is needed to evaluate the optimal position for the sensor placement. Work in this field in the Ph.D. dissertation of a current CMU robotics graduate student.

5.3 Methodology for identifying debris

The identification of debris will be heavily dependent on the sensors chosen and the nature of the debris being sought. The key issue will be to distinguish the debris from the natural, background terrain. We propose a combination of magnetic sensors, high frequency surface radar, visual light and infrared cameras as our sensor suite. It is the use of a variety of sensing modalities that will allow the successful identification of debris in a natural terrain setting.

The identification of metallic debris will be significantly easier than the identification of non-metallic debris. A typical operating scenario for the BTR, assuming the presence of metallic debris is as follows:

- The BTR navigates along a predetermined path, using the trajectory and path planners, within a user specified area that is suspected of having debris
- The BTR follows the predetermined path until the magnetic sensors or radar indicate the presence of metallic objects
- Imaging sensors are then used to acquire high resolution maps of the local area
- The data manager processes the data and assess the existence of debris
- The higher level portion of the mission manager will then take over to modify the trajectory and so the BTR can more closely examine the suspected debris
- Video images transmitted to the control base will be used by the mission controller to assist the robot in its search (supervised control) or for later analysis
- After identifying and tagging the debris, or failing to find debris, the BTR returns to its original trajectory

The speed calculations made in Section 2.2 are still valid even though more emphasis seems to have been placed on the magnetic/eddy current sensors in this proposed scenario. Regardless of the types of sensors used, if an area is suspected of being contaminated with debris, a high resolution map of the area is desirable for further study, so the imaging sensors are the primary, speed limiting sensors. The reason that the magnetic sensors/radar don't impose speed limits is that these sensors are used for course sampling, simply to detect the presence of metallic objects, and can therefore be moved at high speeds without impacting accuracy.

Experiments will be required to determine appropriate sensing modalities for non-metallic objects. This is important as the use of composite materials and plastics for the manufacturing of satellites, etc., continues to increase.

6 Support Systems

The BTR is transported to the operation's site aboard a wheeled vehicle, typically some slightly modified army vehicle capable of driving on unimproved roads. This vehicle also serves as a communications relay between the robots and the controlling ground station. This scheme was chosen because it allows the use of very low power, short distance, telemetry systems on board the BTR's, a desirable feature since a such a link is more easily secured than a direct to base link or even a satellite relay link. The reason this link is more secure than a satellite relay link is that the BTR has limited capabilities, and fine pointing an antenna to precisely hit a satellite would be very difficult, thus, a broader beam would be needed.

The BTR's are deployed by a two man crew, who are responsible for field maintenance of the robots. These maintenance tasks include vehicle check out procedures, cleaning and sensor calibration if required. In addition to maintenance tasks, the crew will be responsible for recovering any robots that may fail during the course of the site survey. This recovery will be carried out using a commercial ATV fitted with a small trailer. Fast robot recovery and recommissioning will be a critical issue, especially if there is a time constraint and a small number of robots are used. Finally, the crew is responsible for establishing and maintaining a satellite link to the control station. Unlike a satellite link from a BTR, this link can be secured since the base is stationary and a large antenna can be used.

The control station need not be proximate to the site to be surveyed because of the telemetry scheme planned. Thus, a facility can be set aside for the purpose of controlling a task force of BTR's. This facility will include

- video monitoring equipment - for downlinks from the on-board imaging sensors
- high-end computer workstations - for simulation so plans can be approved before a BTR ventures into a particularly hazardous region
- manual control over-rides - for controlling the BTR manually if deemed necessary

In addition, this facility may also serve as the storage facility for the BTR. This storage facility must include the necessary equipment for robot repair and extensive sensor calibration.

7 Conclusion

We have presented a rationale and a design for a robotic concept capable of operating and carrying out missions in barren terrains. Specifically, the design is a novel form of beam walker that presents advantages of simplicity in configuration while giving high performance. Power and motion studies show that efficiency is high and it's amenability to robotic perception and planning technique makes navigation in unstructured environments tenable.

We are continuing not only to develop the design but to embark on the production of a prototype vehicle with support from NASA. We aim for a multi-week mission to provide performance measurements of autonomy and reliability.

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