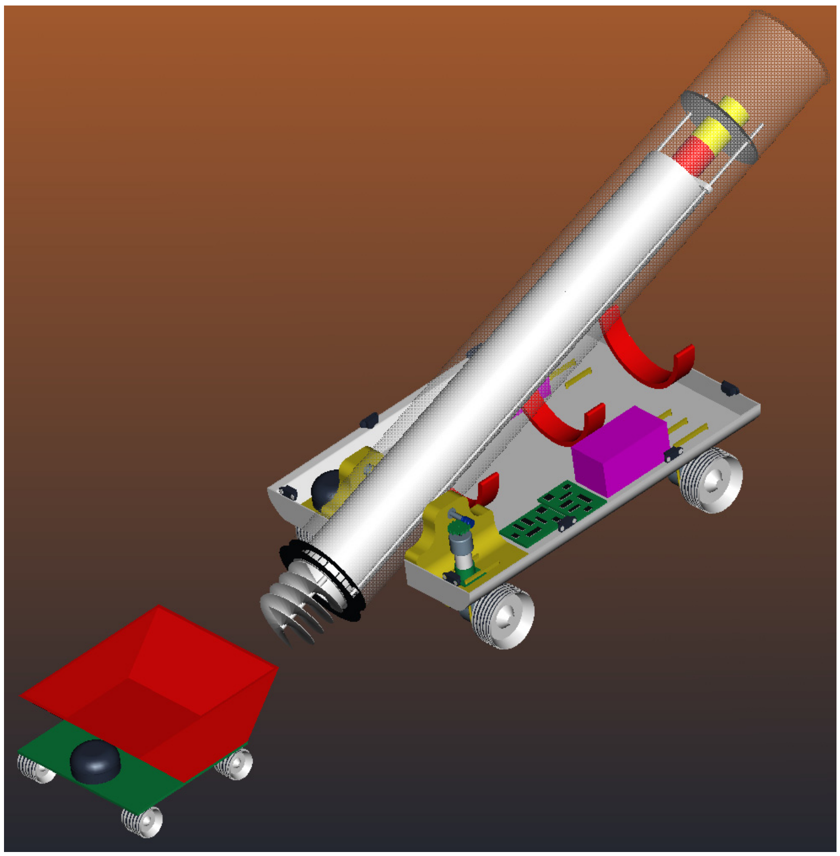
Integrated Robotic Team for Martian Water Collection



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Abstract

This paper is in response to a request for papers from the Lunar and Planetary Institute for the annual conference of its Revolutionary Aerospace Systems Concepts–Academic Linkage program. An integrated robotic team for the collection of subsurface Martian water ice was designed, based on the 2001 Mars Odyssey discovery of the signatures of a significant amount of water ice on Mars. Gamma-ray spectrometer readings indicate that in large regions near the Martian poles, the soil between 60 and 100 cm beneath the surface contains 40% to 73% water ice by volume. The extraction and transport of this water would enable human habitation and exploration on Mars because water can be consumed by humans and chemically transformed into hydrogen and oxygen fuel. This study adopted the philosophy that a team of small robots can perform this collection task more efficiently and more reliably than one large, multi-task robot.

A concept was designed for a team of small autonomous robots that traverse the Martian soil to detect, extract, and transport ice to a central holding and processing location. The team consists of drilling rovers that penetrate the Martian surface, collect frozen water and soil, and deliver this ice/soil mixture to quicker, less massive transporting rovers.

A top-level design of the entire robotic team was produced. For the drilling rover, initial specifications were determined for the structure, drive train, command and data handling, navigation, communication, and power subsystems. The water detection subsystem of the transporting rover was also given initial specifications. The robotic team's water collection method was then designed in more detail. The system consists of a 10 cm auger followed by a 100 cm collecting tube that drills to a depth of 100 cm and to collect all of the encountered dry and ice-rich soil. The system then transfers only the ice-rich mixture to a transporting robot, which delivers it to the processing plant. Engineering drawings were created for this water collection design and for the design of the drilling rover.

This preliminary design for Martian water collection calls for a team of 30 drilling robots and 10 transporting robots. The team has a total system mass of 700 kg and the capability of collecting 65000 kg of water in a 180-day water collection mission.

1. Introduction

1.1 Mars Odyssey Finds Water

Gamma-ray spectrometer readings from the 2001 Mars Odyssey spacecraft indicate that the top 1 meter of Martian soil is rich in hydrogen poleward of 60° south latitude and in areas poleward of 60° north latitude. This identification of hydrogen suggests the presence of large amounts of water ice in the top 1 meter of soil. The discovery that this hydrogen-rich layer corresponds to areas of predicted ice stability based on atmospheric and soil conditions strengthens the argument for the presence of ice. The ice is more highly concentrated in the lower portion of this top meter of soil, with a starting point that decreases in depth with increasing latitude, beginning at approximately 60 cm near 60° north and south latitudes. By weight, the ice constitutes 35 ± 15% of the subsurface material, which corresponds to a range of 40 to 73% ice by volume[1].

1.2 Implications of Water Discovery

These findings have a direct impact upon the possibility of human exploration of Mars. In 1997, the Mars Reference Mission was created by NASA to lay out a preliminary plan for the first human missions to Mars, as well as to outline the necessary technologies that must be developed to carry out such missions. Two of the main objectives of the Mars Exploration Program are to conduct: (1) "Human missions to Mars and verify a way that people can ultimately inhabit Mars" and (2) "Applied science research to use Mars resources to augment life-sustaining systems," also referred to as in situ resource utilization (ISRU). Additionally, there is a focus on relying on automation, especially with regards to ISRU systems, which must be operational even before humans leave Earth. NASA plans on using Mars' in situ resources mainly to produce propellant, which will fuel the astronaut's ascent vehicle used to return to orbit at the culmination of their mission. These resources will also be used to provide "fuel for surface transportation, reactants for fuel cells, and as backup caches of consumables for the life support systems." As of 1997, the plan was to use the Martian atmosphere for the production of these necessary elements, and to import hydrogen from Earth. However, "should sources of indigenous and readily available water be found, this system could be simplified." The presence of water ice is thus a significant discovery that will eliminate much of the need for transporting resources from Earth, thereby reducing launch mass and mission costs[2].

1.3 Concept for Integrated Robotic Team for Collection of Water

The Mars Reference Mission has also identified extraterrestrial mining techniques and resource extraction processes as two of the technology developments required to make human exploration feasible[2]. This paper will address these technology needs by designing a system that will detect, extract, and transport the subsurface ice to a central holding location where it can be processed to create propellant and compounds for crew life support. This system will consist of an autonomous team of small robots that will traverse the Martian soil, extracting, collecting, and transporting the ice.

1.4 System Strategy

The unique aspects of this concept are its method for water collection and its focus on teamwork and distribution of tasks. A team of small robots is preferred to one large robot for several reasons. First, utilizing a team of small robots will enable mission costs to be reduced. Second, it will provide a more robust system by significantly reducing the impact of single-point failures. If multiple robots operate in parallel, then the failure of one individual robot will not cause the mission to fail. Furthermore, contingency can be factored into the system so that the water collection quota will be reached even if several robots fail. Third, a team of small robots has the advantage of being able to cover more surface area at one time than one large system. The area that one large robot can cover is limited to its rate of water extraction and movement. For a team of robots, however, this rate is multiplied by the number of robots, allowing for more water collection at the same time. The gamma-ray spectroscopy of Mars penetrated only 1 meter into the Martian soil, so the existence of water ice has only been confirmed down to 1 meter in depth. Because the depth of the extraction is limited, a team of robots that covers a large horizontal area will extract more water than a single system that can reach high vertical depths.

1.5 Design Focus

The focus of this design will be on the water collection system, since this is the new technology that makes the robot unique from other Mars rovers. The paper focuses on the requirements for the system as a whole, and the design iterations and final results for the water collection device. Because the other subsystems are driven by the design of the water collection system, they are currently in a preliminary design phase, and are briefly outlined in this paper.

2. Approach

To address the problem of subsurface frozen water collection via a team of small robots, it is necessary to follow a systems engineering approach. With this method, the objectives of the mission are established, and from these, the top-level requirements of the system are derived. Using the top-level requirements as guides, the actual design process begins. Iterations are carried out for each subsystem; possible methods for achieving the mission objectives are suggested, studied, and eliminated if requirements are not met. In the end, the design is based on the method that best meets the objectives and follows the requirements. Currently, the concept for the integrated robotic team is in the design iteration phase. The water collection subsystem has been through several iterations, but for each of the less revolutionary subsystems, only one or two designs have been studied.

2.1 Top-Level Requirements

According to this systems engineering approach, the first task is to define the objectives and top-level requirements of the robotic system. The essential functions of the system are mobility, water detection, water extraction, water transfer, and water transport. The ultimate goal is a system that improves upon the Mars Reference Mission while performing these functions to achieve the objectives of the Mars Exploration Program. Improvement on the Mars Reference Mission includes an increase in fault tolerance and lower mass, volume, and power consumption levels.

A review of NASA's most recent plans for Martian ISRU establishes a basis for comparison. The 1997 Reference Mission document outlines an ISRU plant concept that consists of two ISRU plants, together producing 23200 kg of water for crew members and 20200 kg of oxygen and 11600 kg of methane fuel for each Mars Ascent Vehicle (MAV). These ISRU plants are designed to produce enough fuel for two missions. Using gases from the Martian atmosphere and hydrogen transported from Earth, the plants combine the Sabatier, CO_2 electrolysis, and H_2O electrolysis processes to produce the methane and oxygen and water by-product. The combined mass of the plants is approximately 7100 kg, their total volume can be assumed to be on the order of 100m^3, and their total required power is on the order of 100 kW [2]. While it provides some detail about utilization of the resources of the Martian atmosphere, the Reference Mission document does not address any sort of transport of Martian regolith. NASA's 90-Day Lunar/Mars Study does, however, provide specifications for a mining excavator/loader vehicle, a hauler vehicle, and their power system. The combined mass of these vehicles exceeds 4500 kg, and their total volume is at least 36 cubic meters[3]. Considering together the atmospheric ISRU plants of the Reference Mission and the regolith movers of the 90-Day Study, NASA's current plans for Martian resource utilization involve a mass, $m_{current}$, of more than 11600 kg ($m_{current} \approx 7100$ kg + 4500 kg) and a volume of more than 100 m^3.

Decreasing the mass and volume by a factor of eight would comprise a significant improvement on the current NASA Martian ISRU concept. A mass decrease would reduce the payload mass of the vehicle that transports the robotic system to Mars and would therefore reduce the fuel requirements and launch costs. According to this eight-fold decrease goal, the first system requirements are that the water collection team's total mass, m_{max}, remains under 1500 kg ($m_{max} \approx m_{current}/8$) and its volume remains below 12 m^3.

Based on the amount of methane and oxygen fuel required by the Reference Mission, it is reasonable to assume that 5000 kg of liquid hydrogen will be needed to ascend to Martian orbit. To produce 5000 kg liquid hydrogen, 45000 kg of water are needed. The 23200 kg of water required by the Reference Mission for crew life support system caches also still must be collected. Accordingly, the next requirement is that the robotic team delivers 68200 kg during the mission's timeframe, which was set at 180 days. Such a delivery requirement dictates a delivery rate of approximately 15 kg of water per hour, based on a continuously operating system.

Table 2.1 Mission Objectives for Integrated Robotic Team for Martian Subsurface Water Collection

Essential Functions	Other Objectives
- Mobility - Water detection - Water extraction - Water transfer - Water transport	- Achieve objectives of Mars Exploration Program - Improve on Mars Design Reference Mission

Table 2.2 Top-Level Requirements for Integrated Robotic Team for Martian Subsurface Water Collection

Metric	Requirement
Mass	< 1500 kg total
Volume	< 12.5 m^3 total
Water Delivery	(68200 kg in 180 days) + 100% Contingency ≈ 30 kg/hour

2.2 Mission and Environmental Assumptions

In addition to the top-level system requirements that have been defined, there are certain mission and environmental assumptions that must be made in order to begin the design of the robotic system. These assumptions are listed in Table 2.3.

Table 2.3 Assumptions for Martian Environment for Martian Water Collection Mission

Issue	Assumption
Landing Site	60°N, 240°E (±5°)
Elevation	3000 m below sea level[4]
Composition of Ice Layer	40% to 73% ice by volume
Depth of Ice Layer	60 cm to 100 cm
Water Collection Area	85 m x 85 m
Temperature	-75° C to 0° C
Air Pressure	6.55 mb to 6.85 mb
Wind	Less than 10 m/s with frequent afternoon dust storms
Gravity	3.7 m/s^2
Dry Soil Grain Size	0.1 µm to 1500 µm
Dry Soil Density	1.2 ± 0.2 g/cm^3 to 1.6 ± 0.4 g/cm^3

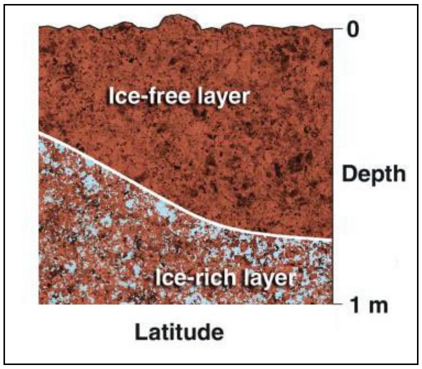

Figure 2.1: Martian Subsurface Model Resulting from Mars Odyssey Findings[5]

The landing site was chosen in the Northern hemisphere because of the less rocky and mountainous terrain that it affords, facilitating landing and mobility for the robotic team. The latitude value of 60° N was selected because at higher latitudes, the presence of a seasonal carbon dioxide cap would hinder water detection and collection, and at lower latitudes, the concentration of ice decreases[6]. The longitude value of 240° E was chosen because it lies in the region that is closest in elevation to the landing sites of Viking (1976) and Pathfinder (1997). At these landing sites, the air pressure was above the triple-point of water, which is necessary for liquid water to be sustained without artificial pressurization. Additionally, this landing site corresponds to one of the areas where Mars Odyssey findings predict the presence of subsurface ice[1]. From these findings, it can be assumed that at the chosen landing site, frozen water comprises 40 to 73% of the soil, by volume, at depths between 60 and 100 cm. At this depth, the soil temperature does not exceed -73° C[6]. The composition of the subsurface regolith is not homogeneous; therefore, the robotic system will seek out areas to extract water that are greater than 50% ice by volume, in order to maximize the efficiency of the system. In order to extract 65000 kg of water, an extraction area of 85 m by 85 m is needed. This calculation assumes a 50% efficiency in extracting ice from the subsurface, and it assumes that only 10% of this area is tapped for water. This 10% value was chosen because the percentage of the subsurface that exceeds 50% ice by volume is unknown and because mobility would be hindered if the entire collection area were littered with craters.

The environmental conditions that the robotic system will experience are based upon measurements taken by previous robotic missions. The air pressure and temperature ranges are based upon those experienced by Pathfinder[7], which landed at 19.13° N latitude and 326.78° E longitude. Although temperatures above 0° C are relatively common during summer afternoons, they only last for a few hours. Winds are generally less than 10 m/s, but afternoon dust storms are fairly common. The surface soil conditions were analyzed by Pathfinder and the Viking landers, and because they were are similar, it has been assumed that the soil in the Northern hemisphere is uniform in all locations[1]. The near-surface regolith contains a mixture of soil that is relatively coarse-grained and mostly igneous in origin and soil that is mostly fine-grained and dominated by some mixture of palagonite and clays[6]. Based on JSC Mars-1 (Mars simulated soil)[8], the grain size ranges from 0.1 to 1500 μm, and its density ranges from 1.2 ± 0.2 g/cm^3 to 1.6 ± 0.4 g/cm^3. The water collection area has a top layer of dry dust strewn with boulders. The near surface soil is generally dry, but may have from a few tenths to a few percent of chemically bound water[6]. Because no rover has analyzed the composition or nature of the soil below the surface, it is assumed that the soil is uniform in the top 60 cm, and the soil that is mixed with the ice layer is also similar in composition to the surface layer.

An additional assumption was made concerning the existing space system architecture at Mars. It is assumed that by 2025, the projected time frame of this mission, a constellation of global positioning system (GPS) satellites will be in orbit around Mars[9]. Thus, any GPS-equipped vehicle on the surface of Mars can receive signals from these satellites to ascertain its position on the Martian surface.

3. Results

With all of the requirements determined, designs for the robotic team can be considered. Because the water collection system is the unique function of the robot, its design is studied first and used to drive the design of the remainder of the robot. The design that resulted from this study consists of a team of drilling rovers that penetrates the Martian surface, collects frozen water and soil, and delivers this ice/soil mixture to quicker, less massive transporting rovers. Upon choosing this water collection system, the rest of the robots' structure and functionalities can be designed. In the following sections are the specifications for each subsystem of the robotic team. The general strategy of the robotic team is outlined first. The physical subsystems are then described, beginning with the water collection system. The rationale behind the design of the water collection system is given in detail.

3.1 Teamwork and Strategy Subsystem

The chosen method for water collection requires a team of drilling rovers that is capable of extracting 30 kg of ice every hour (see Table 2.2). To obtain 30 kg of ice, the team must collect 65000 cm^3 of ice/soil mixture. This required volume, V, of ice/soil is calculated with ρ, the density of ice; C, the composition of the mixture; and m, the required mass of ice:

$$V = \frac{m}{\rho C} = \frac{30000g}{(0.931\ g/cm^3)(50\%)} = 64445\ \text{cm}^3 \approx 65000\ \text{cm}^3. \quad (3.1)$$

This design assumes that the driller rover can efficiently collect ice/soil from 30 cm of the 40 cm-deep ice-rich layer. With an auger diameter of 10 cm and a collection height of 30 cm, 30 driller rovers are needed to collect 65000 cm^3 of ice/soil mixture, assuming that each robot performs one cycle per hour. The number of drills, N, is calculated with V; d, the auger diameter; and h, the height of the ice/soil mixture:

$$N_{drill} = \frac{4V}{\pi d^2 h} = 27 \approx 30. \quad (3.2)$$

Transport rovers complete the job that these 30 driller rovers begin. The transport rovers simply receive the ice/soil mixture from the bottom section of the driller's collection tube and deliver it to the central processing station. Figure 3.1 illustrates this cooperation between the driller and transport rovers. It is reasonable to assume that the transporter's delivery of material will occur at a rate 3 times faster than the driller's extraction; consequently, 3 times fewer transport rovers than driller rovers are needed. Assuming this 3-fold relation between operating rates, 3 driller rovers are serviced by every 1 transport rover. The required volume of the transporter's holding tank, $V_{transport}$ is then:

$$V_{transport} = 3 \times \frac{V}{N_{drill}} = 3 \times \frac{65000cm^3}{30} = 6500\ \text{cm}^3. \quad (3.3)$$

The linear dimensions of the transporter robot can then be on the order of (6500 cm^3)$^{1/3}$, or 19 cm x 19 cm x 19 cm.

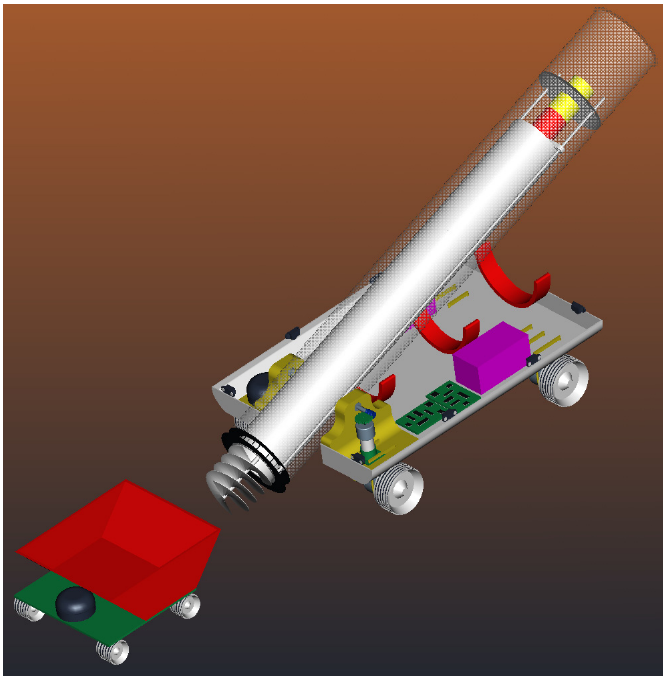

Figure 3.1 Cooperation of Driller and Transport Rovers for Martian Subsurface Water Collection

3.2 Water Collection Subsystem

As water collection is the team's unique function, design efforts were concentrated on the water collection system. An extensive iterative process was followed, and several possible designs emerged as the key design issues were explored. This section explains the design options that were considered and presents the final specifications that resulted from the iterative design process.

3.2.1 Water Collection Design Iterations

Figure 3.2 outlines the design iteration process that was followed for the water collection system. The figure shows each design problem that arose, the possible solutions to each problem, and the methods considered for implementing each system. The chosen solution for each problem is shaded, and arrows point to the subsequent decision.

3.2.2 Explanation of Water Collection Decisions

The final design was chosen to minimize both the complexity of the system and the amount of power required by the system. Complexity can be reduced by limiting the number of moving parts and mechanical systems, which is critical in a system that must function autonomously and without the ability to make repairs. Additionally, low complexity decreases the chances of fatigue failure, which is an important consideration for a system that is required to run continuously for 180 days.

3.2.2.1 Removal of Dry Soil Layer

To access the ice beneath the top layer of dry soil, two solutions were considered: (1) exposing an entire region of the ice layer by clearing away large portions of the top layer of soil or (2) penetrating through the top layer of dry soil each time a section of ice is extracted. The latter option was chosen because of the difficulty of clearing away large areas of dry soil. The main difficulty arises from the soil's lack of stability. The frequent dust storms on the Martian surface also pose the danger of filling in the quarries with dust and burying the robots. As a result, the optimal design consists of each robot independently drilling through the top layer of dry soil each time it removes a section of ice.

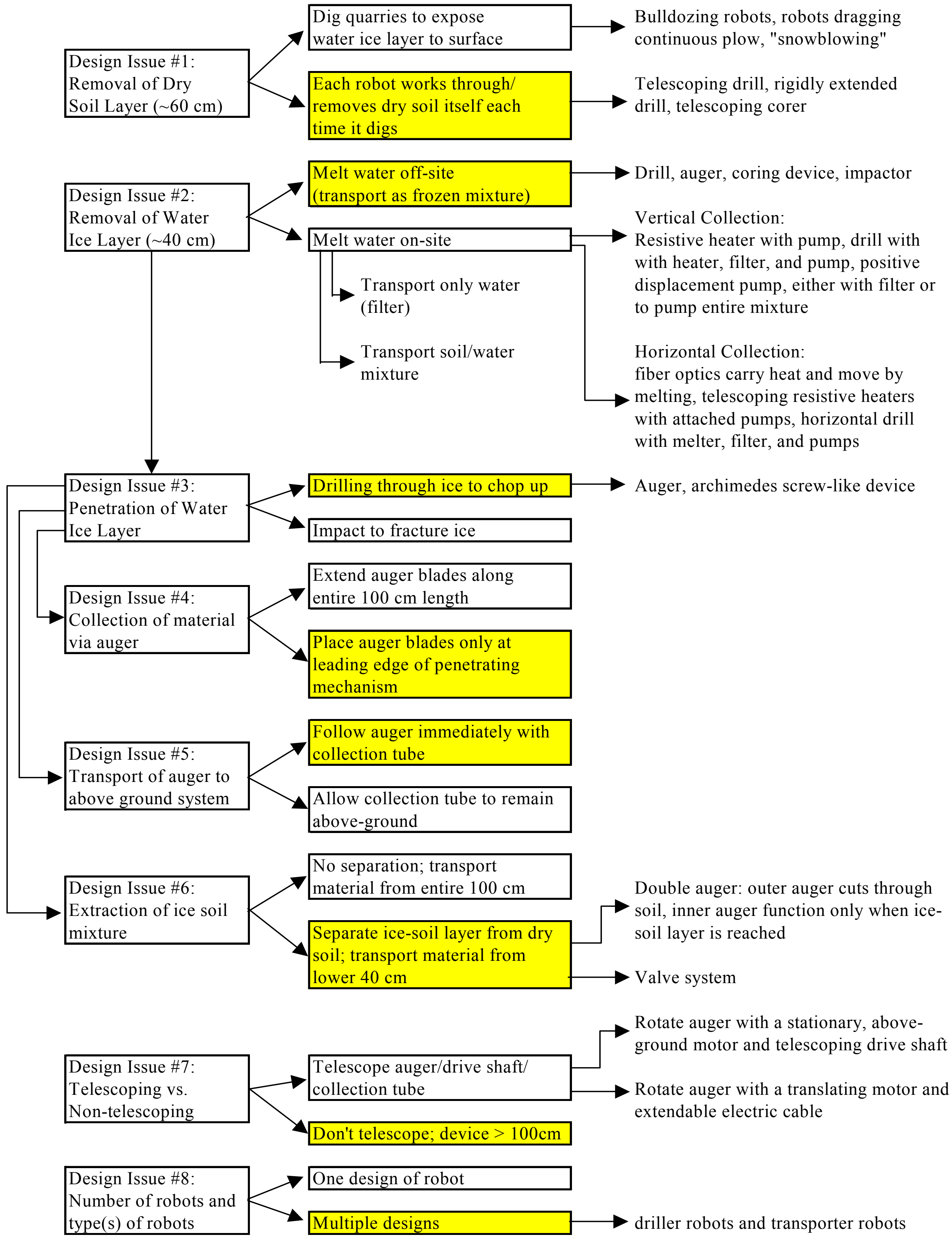

Figure 3.2 Design Issues, Solutions, Implementations, and Decisions in Determining a Method for Martian Water Collection

3.2.2.2 Removal of Water Ice Layer

To extract the ice, there were also two general solutions: (1) melting the ice on-site or (2) melting the ice off-site. The advantages to having each robot melt its own water included carrying less material back to the central location and reducing using only heating elements rather than moving parts. Several problems arose from this design, however. First, a heating element alone would not be sufficient; a drill-like device would still be necessary because the composition of the ice-rich layer is up to 50% soil by volume. Next, separation of the water from the soil would require a filter, which would have a high likelihood of clogging because of the small particle size of the soil, as small as 0.1 microns. Such small particles tend to settle very slowly, and typically have Reynolds numbers less than one. These flows are generally dominated by viscous effects, and Stokes showed that the velocity of a one micron particle is approximately equal to:

$$V_p = \frac{2\rho g R^2}{p\mu} \approx 0.15\,{}^{mm}\!/_{s} \tag{3.4}$$

Due to Stokes drag, the smallest particles encountered by the filter would travel much slower than the rest of the flow, causing the filter to clog. Because of this problem, it would have been necessary to carry back at least some of the soil. Third, the containment of liquid water would require a regulated environment because at the Martian atmospheric pressure, liquid water only exists between approximately 0 and 10°C. Finally, simple energy calculations reveal that providing the heat of fusion to melt the ice requires significantly more energy than fracturing and lifting the frozen ice and soil mixture. To melt 300 g of water at 0 C, 100200 J are required, while energy only on the order of 100 J is required to fracture and lift the 800 g of frozen soil that contains 300 g of water. The following calculations show how these values are derived.

$$E_{melt} = m_{ice}\Delta h_{fusion,ice} = (300g)(334\tfrac{J}{g}) = 100200J \tag{3.5}$$

$$\begin{aligned} E_{mechanical} &= E_{fracture} + E_{lift} = w_{frozen\,soil\,fracture}V_{soil} + m_{soil}a_{Mars}d_{lift} \\ &= (165\tfrac{kPa}{m^3})(644.5cm^3) + (300g)(3.69\tfrac{m}{s^2})(1.25m) \\ &= 106J + 1.4J = 107J \end{aligned} \tag{3.6}$$

(3.6)[10]

Melting the ice off-site by carrying the frozen ice/soil mixture back to the central holding location is the preferred option. Although this option requires carrying the entire ice/soil mixture, this transportation would be necessary even if the ice is melted on site. Because the robot must get through the dry soil layer in either case, an attractive method is to use the same tool to extract both the dry soil and ice/soil layers. An auger is an ideal tool for accomplishing this task, since it serves both to drill through the soil and to displace it upwards simultaneously. An auger will granulate the ice/soil mixture as it drills, making it easier to transport and store. The torque required to push a 10 cm-diameter drill through soil is significant. Typical small cordless drills deliver a torque of 8 N-m for a 1cm drill bit. This corresponds to 80 N-m for the rover's 10 cm auger. At high rotational speeds, achieving a torque of 80 N-m would require more power than is available ($P = T\omega = 1780$ W for ω of just 200 rpm). However, high rotational speeds are not necessary. If the auger can descend 0.5 cm in one revolution, then a speed of 20 revolutions per minute would enable the auger to penetrate 100 cm in just 10 minutes. A 10-minute drilling time fits into the requirements of the mission, and a speed of 20 rpm requires 178 W of power, which achieves the design goal of minimizing the required power.

3.2.2.3 Design of Auger

The first consideration when designing the auger device was whether or not to extend the auger the entire 100 cm length of the hole being drilled or to place a shorter auger at the end of a drive shaft. The initial incentive for creating a 100 cm auger was to ensure that all of the material would be transported upwards to the surface. However, the 6 kg mass required by an auger of that length would cause the robot to exceed its mass constraints. Additionally, a full-length auger is not required for the soil to be transported upwards.

The auger will displace soil upwards toward the surface as it drills. A collection tube or tank will then collect the material being displaced. While a tube or tank that remains above the surface is the simplest option, a support structure would be necessary to maintain the structure of the hole created by the auger. Because the drive shaft will have a smaller diameter than the hole created by the auger, the hole will collapse behind the auger as it travels downward through the dry soil layer. Therefore, a collection tube that follows the auger into the soil is the preferred option.

3.2.2.4 Separation of Ice/Soil Layer

It would be ideal to separate the top 60 cm of dry soil from the bottom 30 cm of ice/soil mixture. This separation would require fewer trips to the central holding tank or decrease the size of the storage tank on each robot. Two possible design iterations were rejected based upon the complexity of the systems. The first involved two augers, one inside the other. The inner auger would be covered while the outer auger drilled through, collected and disposed of the dry soil. Upon reaching the ice-rich layer, the outer auger would be covered, and the inner auger would drill through and collect the ice-rich soil. The second design required only one auger, and would use a valve to direct the dry soil out of the robot and the ice-rich soil into a holding tank on the robot. Both designs would add mechanical complexity. The alternative design that was chosen consists of a non-telescoping auger that expels the desired bottom 30 cm into a transporting rover and the unwanted top 60 cm back to the Martian surface.

3.2.2.5 Telescoping of Auger versus Non-telescoping System

Another design issue involves the choice between a telescoping and a rigid non-telescoping drive shaft/collection tube. Telescoping allows for a more compact robot design with the ability to drill to the required depth. However, telescoping adds complexity and multiple moving parts. Additionally, a telescoping drive shaft and collection tube would have to be covered with a shroud to prevent mechanism-locking from fine soil particles. The trade-off is between a compact telescoping design and a larger non-telescoping design. The final design consists of a tube with a length of 125 cm, which contains the non-telescoping collection tube and drive shaft connected to a 10 cm auger.

3.2.2.6 Single Robot Type versus Multiple Robot Types

The design of the water collection robot lends itself to a system that consists of two types of robots: a drilling water collection robot and a water detecting and transporting robot. Because the driller robots' sole purpose is to drill and extract the ice, their mobility becomes less important. These robots can be built with the primary focus on drilling. A second robot will serve as a water detecting and transporting robot. This focus of these robots will be on mobility, and they will be more agile, smaller and lighter.

3.2.3 Preliminary Design of Water Collection System

The chosen water collection method consists of drilling to a depth of 100 cm and collecting all of the dry soil and ice-rich soil encountered in the resulting 100 cm column. This method is implemented with a 10 cm auger followed by a 100 cm collection tube. The tube and auger are stowed horizontally within an outer protective cylinder on the driller rover. When the rover reaches a drilling location, a shoulder motor on the rover drives the cylinder to rotate about an axis normal to its length. When the cylinder is oriented vertically, the rotation ends and the auger becomes operational.

A translating motor drives the rotation of the rigid auger and drive shaft assembly, and parallel lead screws drive the insertion of the collection tube into the subsurface. A roller bearing interface between the drive shaft and the collection tube allows the collection tube to transfer the downward force from the lead screws into vertical thrust for the auger. This bearing is embedded in a disk that is rigidly connected to the collection tube. Cut-outs in the disk allow soil to travel up the collection tube. Because the bearing is fully constrained to the drive shaft in the vertical direction, and the disk is fully constrained to the collection tube in the vertical direction, the drive shaft (and auger) matches the vertical translation of the collection tube. As the auger and collection tube descend into the subsurface, the rotation of the auger directs soil from the top 60 cm and ice-rich soil from the lower 40 cm upwards into the tube. Once the entire column of soil is inside the tube, the lead screws reverse their rotation, and the tube, drive shaft, and auger ascend back into the outer protective cylinder above the surface. The bottom 10 cm of ice/soil mixture remains in the auger blades; this material is allowed to escape back to the surface as the auger retracts upwards. Consequently, a cylindrical volume of ice/soil mixture that measures 30 cm in depth by 10 cm in diameter contains all of the desired water. Once the auger and collection tube have been fully retracted, the rover's shoulder motor pivots the water collection cylinder 45 degrees away from vertical, the transporter robot positions itself below the cylinder opening, and the auger rotates in reverse until the ice/soil layer has been released. Finally the transporter rover drives away, and the auger rotates until the collected dry soil layer is expelled onto the Martian surface.

A ledge that is embedded into the outer cylinder supports both the spool that contains the extendable cable of the auger motor and the motor that drives the rotation of the lead screws. At the bottom end of the outer cylinder, a tightly-fitting guide keeps the drive shaft and collection tube in alignment as they enter the subsurface. Figures 3.3 and 3.4 highlight the main components and dimensions of the water collection device.

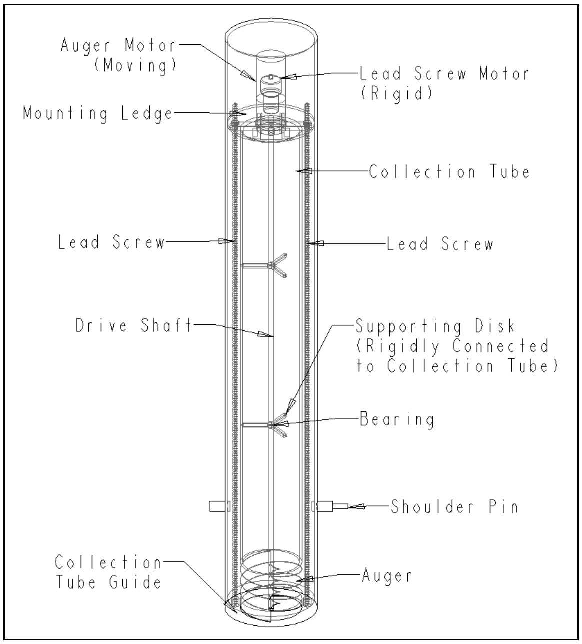

Figure 3.3 Components of Martian Water Collection Device

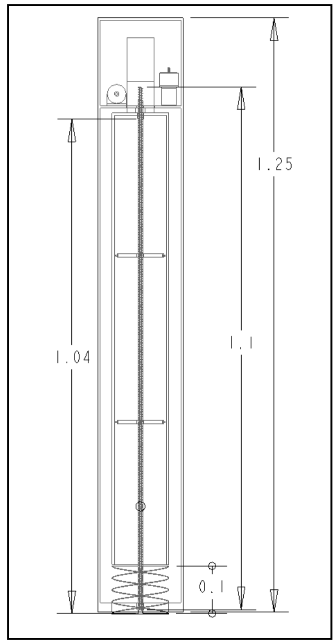

Figure 3.4 Dimensions (in meters) of Martian Water Collection Device

To illustrate better the functionality of the water collection device, Figure 3.5 provides a shaded view, with the outer cylinder transparent. Figure 3.6 shows an exploded view of the outer cylinder, collection tube, and auger. Figure 3.7 details the guide that stabilizes the auger and collection tube as they enter the subsurface.

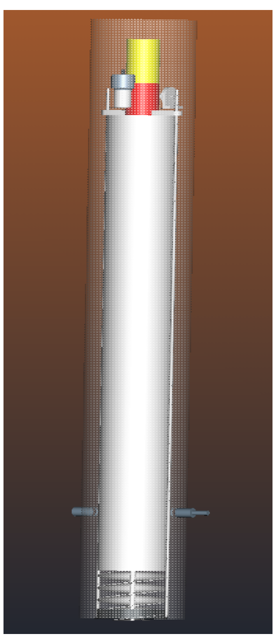

Figure 3.5 Shaded View of Martian Water Collection Device

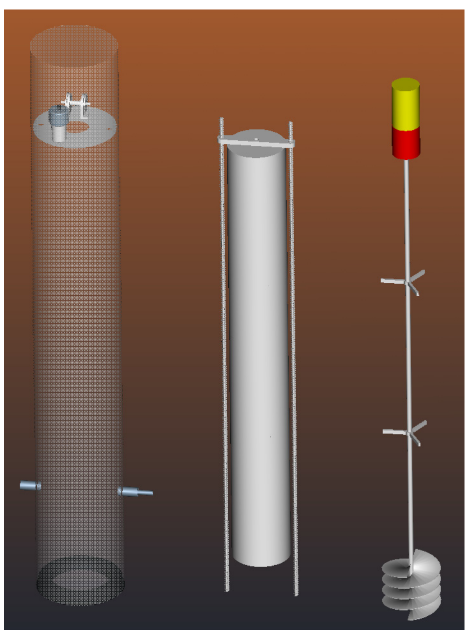

Figure 3.6 Exploded View of Martian Water Collection Device

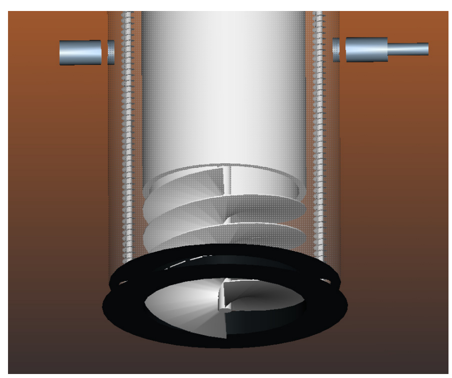

Figure 3.7 Detailed View of Auger Guide on Martian Water Collection Device

3.3 Structure Subsystem

The structure of the drilling rover exists to support, actuate, and transport the water collection device. Its supporting members are comprised of cold temperature resistant metal. The total mass of the rover is 18 kg, and it measures 125 cm, 31 cm, and 50 cm at its longest, tallest, and widest points. In addition to the water collection device, the main components supported by the structure of the rover are the wheels and their motors, the shoulder bearing for the water collection cylinder, the shoulder motor, the Mars GPS device, the feedback and control microcontroller, the high-level microprocessor, and communications transmitter, and 2 125-watt radioisotope thermoelectric generators (RTGs). All of these components will be explained in the subsystem sections that follow. Figure 3.8 displays the rover's general structure and all of its main components, and Table 3.1 lists these components. Figures 3.9 and 3.10 illustrate the basic dimensions of the drilling rover.

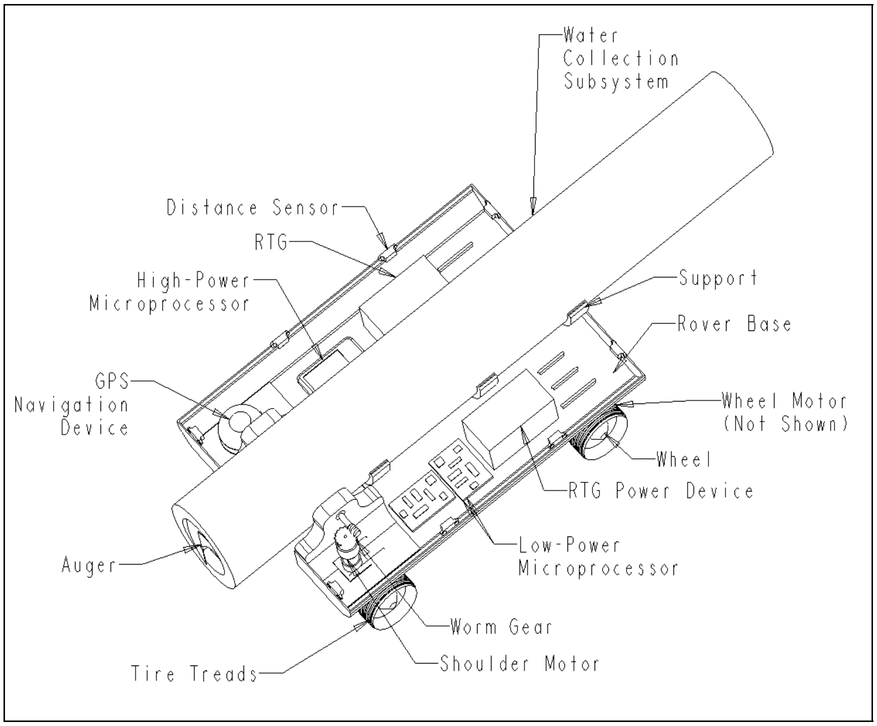

Figure 3.8 Layout and Components of Driller Rover for Martian Water Collection

Table 3.1 Main Components of Driller Rover and their Masses

Component	Mass (kg)
Drive Shaft (98cm)	0.6
Auger (10cm)	0.4
Auger Motor	1
RTG 1	5
RTG 2	5
Tilt Motor	1
Lead Screw Motor	0.5
GPS	0.2
High-power Processor	0.2
Low-power Processor	0.2
Wheel & Motor	0.5
Wheel & Motor	0.5
Wheel & Motor	0.5
Wheel & Motor	0.5
Supporting Structure	2
TOTAL	18.1

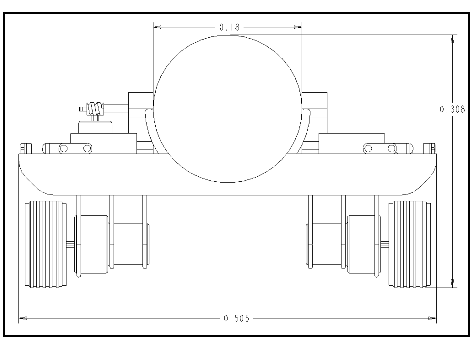

Figure 3.9 Front View of Driller Rover for Martian Water Collection

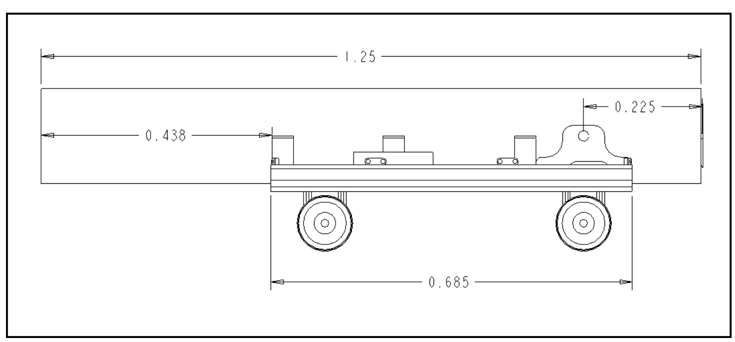

Figure 3.10 Side View of Driller Rover for Martian Water Collection

Figure 3.11 depicts the rover with the water collection device in its operational, vertical position. Figure 3.12 shows a view of the rover with the water collection device stowed horizontally, ready for rover movement. The rover is shown with the non-drilling end in the foreground.

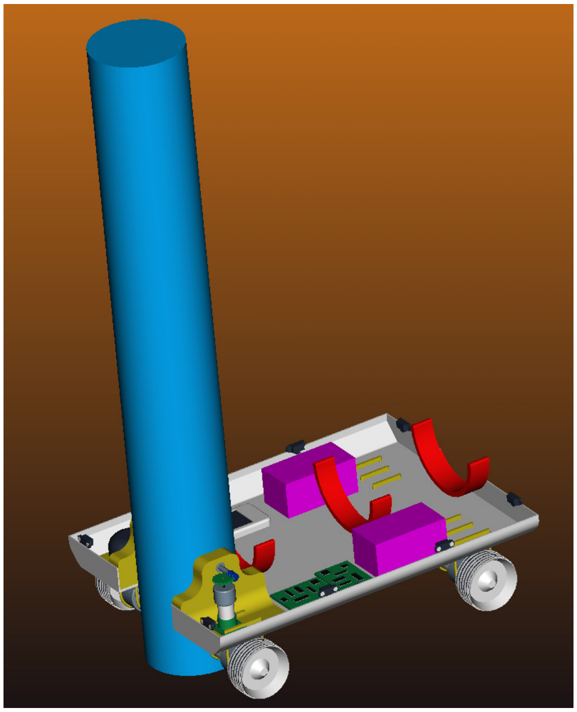

Figure 3.11 Martian Water Collection Rover with Operational Drill

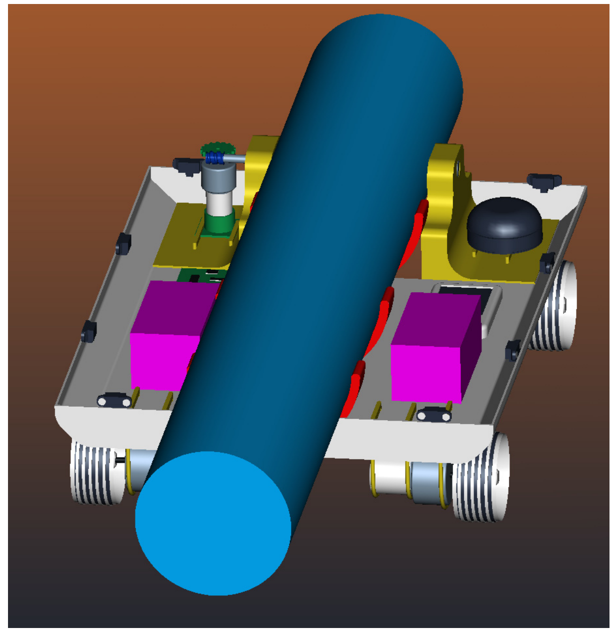

Figure 3.12 Martian Water Collection Rover with Stowed Drill

3.4 Drive Train Subsystem

The drive train of the driller rover will consist of four wheels each driven by an individual motor. They are covered with treads for traction on the Martian soil. To enable the rover to clear any surface obstacle that is 5 cm or less in height, the wheels are 10 cm in diameter. Each wheel motor draws power from the RTGs based on the signal it receives from the rover's microprocessor. Figures 3.11 and 3.12 depict each wheel motor directly shafted to its respective motor. In further work, the design may place the motors on the rover base, directly above wheels, with right-angle gears providing the connection between the motors and the wheels. Because the rover is only required to travel distances less than 85 m and can take several minutes to travel those distances, it needs only to achieve velocities on the order of 0.5 m/sec. For wheels that are 10 cm in diameter, the motors need to operate at the low speed of 100 rpm.

3.5 Command and Data Handling Subsystem

The feedback and control system of both the drilling rover and the transporting rover are run by an embedded microcontroller, which handles a limited set of time-critical tasks. This feedback and control processor controls the speed and movement of the robot, drilling mechanisms, water detection, object avoidance, and docking. For such processes, latency is a prime consideration.

Computationally intensive tasks such as data storage and processing, navigation, drilling site selection optimization and communication require a processor with greater computational power than the microcontroller for hardware control. Consequently, on each type of rover, a second processor handles these tasks. This extra complexity incurs greater power usage, but power consumption of this higher level system can be minimized by powering down components or scaling the clock speed of the processor when full capabilities are not required.

Designing the system with two separate microprocessors is an attractive option because it increases the fault tolerance of the system. Traditionally, each robot would be simplified and much of this processing would be done by a central computer. A simplified robot and central computer would also simplify coordination between teams of working robots. However, a central control station giving out orders to all robots introduces a single point of failure in the system. If each robot can instead make its own decisions, that responsibility is distributed evenly among the robots. A second disadvantage of a central control station is the higher power that it would require. If it is considered how microprocessor cycles per mW have increased linearly over the past 20 years, a significant power savings can be seen since RF uses a virtually constant amount of power per amount of data passed.

3.6 Communications Subsystem

The water collection team uses wireless communications to allow a team of robots to work on shared tasks. Both types of robots broadcast messages to the entire collective through an ad hoc peer-to-peer 2.4 GHz network. The communication module has enough RF power output to be broadcast over the entire water extraction area. This model allows the rovers to share and aggregate vital information, such as water concentration and obstacle avoidance data. This method has been chosen because of the availability of hardware and software modules to handle the physical and logical layers with reliable performance and low power usage.

3.7 Navigation Subsystem

The navigation system works under the assumption mentioned above that GPS satellites are in orbit around Mars. Each driller rover and each transport rover contain a GPS receiver that is supplied with differential correction factors over the wireless network from a central computer and GPS receiver. The motivation for differential GPS is to increase the accuracy of the mobile GPS stations. The design assumes that the base station is located at a fixed location so error correction factors can be calculated by comparing the known position to the position obtained by the GPS receiver. These correction factors are subsequently applied to all the robots to achieve the resolution needed to reliably locate other robots on the Martian surface. While the base station could represent a single point of failure, it is assumed that sufficient redundancy has been built into the Martian GPS system, as it will be critical to many other mission objectives.

3.8 Power Subsystem

Each driller rover is powered by radioisotope thermoelectric generators (RTG). RTGs are lightweight, compact power systems that are highly reliable. RTGs are not nuclear reactors and have no moving parts. They use neither fission nor fusion processes to produce energy. Instead, they provide power through the natural radioactive decay of plutonium-238, a non-weapons grade isotope. The heat generated by this natural process is changed into electricity by solid-state thermoelectric converters. RTGs enable rovers to operate at significant distances from the sun or in other areas where solar power systems would not be feasible.

Radioisotope power sources are the enabling technology for space applications requiring proven, reliable, and maintenance-free power supplies capable of producing up to several kilowatts of power and operating under severe environmental conditions for many years. Previous space missions that have used radioisotope power sources include the Apollo lunar surface scientific packages and Pioneer, Viking, Voyager, Galileo, and Ulysses spacecrafts. The Mars Reference Mission alludes to plans for a “Dynamic Isotope Power System” that delivers power at a specific power of 9 W_e/kg[2]. Assuming a two-fold increase in technology every ten years, it can be estimated that radioisotope power systems will have specific powers of approximately 35 W_e/kg by the year 2025. Consequently, the driller rover is powered by two 5-kg RTGs, each delivering 125 W_e of power. They deliver a more conservative specific power of 25 W_e/kg. The 250 W_e of power that they deliver is sufficient for all of the rover’s electrical systems.

RTG power sources are superior to other power system options. Solar power is an frequently used option, but to produce 250 W_e of power with 30%-efficient photovoltaic cells, a cell surface area of more than 1 m^2 is required. This surface area A_s is given by:

$$A_s = \frac{P_{required}}{I_{Mars}\eta} = \frac{250W}{(600\,{}^{W}\!/_{m^2})(0.3)} = 1.39\ \text{m}^2\ , \qquad (3.7)$$

where I_{Mars} is the solar flux at Mars and η is the efficiency of the photovoltaic cells. Adding almost 1.5 m^2 surface area to each rover would cause the robotic team to exceed its size limitation. Another drawback of solar cells is that they cannot operate continuously or completely independently. They must cycle through charging and discharging cycles that depend on the length of solar exposure, and they work in conjunction with batteries that store and deliver power when the cells are not exposed to sunlight. These batteries increase the mass of the power system, and the dependence of the photovoltaic power system on sunlight means that continuous operation of the robotic water collection team could not be ensured. Compact, continuously functioning RTGs are desirable over solar cells.

3.9 Water Detection Subsystem

The robotic team depends on the transport rovers to detect water in the near subsurface. The transport rovers be equipped with water detection systems that can determine the regions where the 60 to 100cm-deep portion of the soil contains more than 50% ice by volume. The transport rovers direct the driller rovers to these water-rich locations. The water detection system uses a lightweight, low-power, ground-penetrating radar (GPR) system to probe the Martian subsurface for aqueous slayers in solid state. Advantages of radar include relatively low mass and power, high signal controllability, and high resolution imaging of subsurface cross sections. A GPR operating in two frequency bands centered around 10 MHz and 500-1000 MHz or sweeping through the 10-1000 MHz region, can provide information about the subsurface with high resolution at shallow depths, which is the region of interest. This technique is considered essential for targeting a mobile drill and for providing 3-dimensional geologic context for drill results. GPR can also be used for subsurface hazard avoidance during long rover traverses[11]. The penetration depth of a GPR on Mars is highly dependent on the stratigraphy and lithology of the subsurface layers. The radar responses from geophysical models of surface characterization, soil properties at microwave frequencies, and three-dimensional stratigraphy mapping based on what could be expected on Mars have been simulated by Leuschen et al[12].

In choosing this method, it was first determined that any water detection system must avoid surface contact to minimize the number of mechanical parts and to maximize the area covered. The non-contacting systems that were considered included infrared, neutron, nuclear magnetic resonance (NMR), and electromagnetic radiation such as ground-penetrating radar. Infrared was discounted because the depth of penetration was only a few microns. NMR was not feasible because of the lack of a magnetic field on Mars. The electromagnetic method was chosen because it was simple to implement and the most reliable.

4. Conclusion

The systems design approach to the problem of Martian subsurface water collection attempted to lay out a set of critical mission requirements and then to best meet these through several phases of design iterations and optimizations. The water collection system chosen meets and exceeds every requirement set out at the beginning of the design process. The team of robots has a total mass and volume of 700 kg and 6 m^3 and possess the capability to collect the required mass of water with 100% contingency. These characteristics are marked improvements over the 90-Day Study's plan for a Martian mining excavator/loader vehicle, hauler vehicle, and their power system. Therefore, the team of small robots more efficiently and more reliably meets the task of Martian ISRU by taking advantage of the recent Mars Odyssey discovery. The concept of using a team of small robots proposes a revolutionary approach, improving upon the customary notion that a large robot is required to accomplish such a full-scale task as mining for frozen water on Mars. The integrated robotic team presented in this paper is a concept that should be taken into consideration for future Mars mission that desire a more efficient and reliable approach to autonomous in situ resource utilization.

5. Further Work

As mentioned above, this paper is the result of the preliminary design phase for Martian subsurface water collection. The conceptual design for the robotic team and the preliminary design of the water collection system have already been laid out, and the next phase is to complete the iteration process for the remaining individual subsystems. This includes designing the interface between the various subsystems to ensure that they will function together. Once all of the subsystems have been designed, the final detailed design must be completed, including the selection of appropriate materials and hardware for robust operation in the Martian environment. Particular attention must be paid to thermoregulation, radiation shielding, and protection from dust prevalent in the atmosphere.

While the details are being completed on all of the subsystems, prototyping and experimentation will begin on the water collection system to optimize its design and to ensure its proper functioning. This will include creating a simulated Martian soil and replicating Martian environmental conditions as much as possible. Once the water collection system is built and its interface with the rest of the subsystems has been designed, it will be incorporated into a fully operational robotic system. The final step is to build the transport robot and to demonstrate the ability of the pair of robots to work as a team to detect, collect, transfer, and transport the water.

6. References

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