The Modular Martian MILLIPEDE

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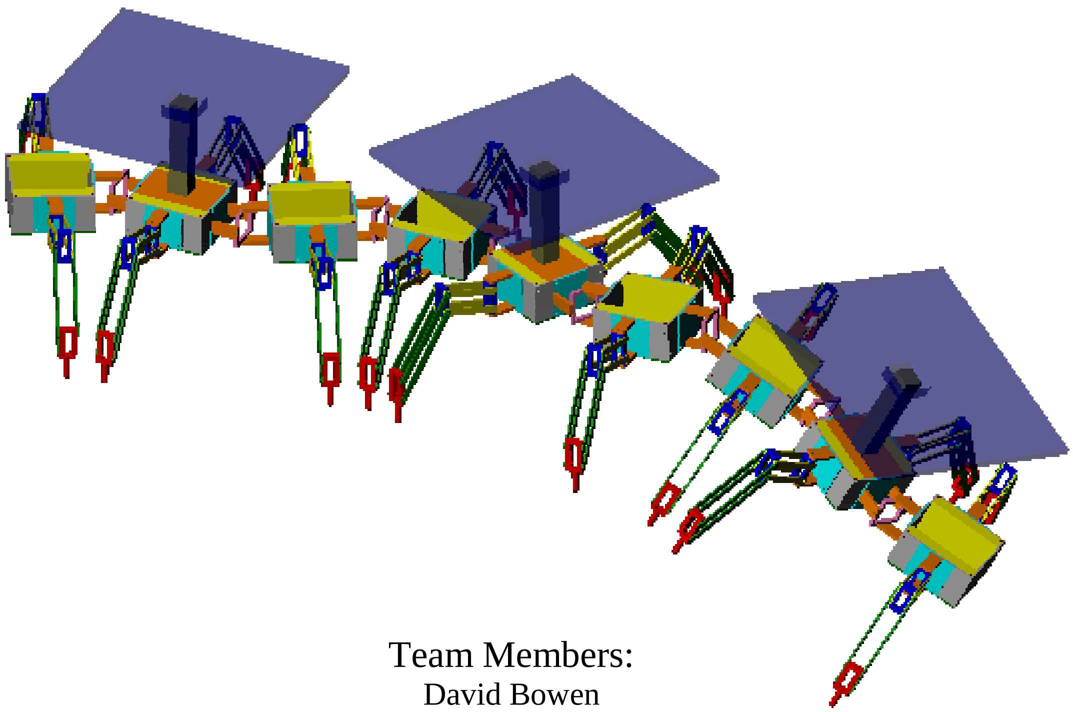

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ABSTRACT

The exploration of Mars is scientifically appealing and can benefit the human race by providing solutions to land and mineral deficiencies. While previous missions have been difficult and costly, some like the Mars Global Surveyor have led to exciting discoveries. As the next logical step, studying the surface of Mars provides many technological challenges, including how to navigate the hazardous desert-like terrain.

Through the use of an insect-like walker, appropriately named the MILLIPEDE, a land-based mission to Mars can become a reality. This vehicle can be used in conjunction with cutting edge scientific experiments to provide almost any function necessary for such a mission. The following document provides the background, design approach and results of each system on the MILLIPEDE. It also explores possible uses of the device and technology used in conjunction with the walker to make it a beneficial tool for surveying Mars.

INTRODUCTION

With every passing day, new advancements in space travel and technology take us closer to reaching the stars. The exploration of other planets offers a wealth of knowledge - not only about the galaxy and its history, but also about life in general. For these reasons, exploring Mars, the closest planet to Earth in likeness and distance, would be the next logical step. One might ask, "Why explore Mars?" Numerous reasons support the decision to explore and study Mars.

For example, Mars could be another location to colonize and to gather raw materials for use here on Earth. More specifically, Mars could contain water. This is a valuable resource and an essential ingredient in the creation and maintenance of life. Therefore, the possibility that Mars could support life is conceivable. That alone is an extremely important reason for conducting research and planning missions to better understand Mars.

Scientists at NASA are in the process of creating a living document describing a future manned mission to Mars. NASA is currently able to study and explore Mars only from afar by using satellites and landing semi-autonomous vehicles. These tools collect data and send the information back to be interpreted by scientists and engineers. This data is then used to refine the mission's objectives detailed in the living document. Hence, if the means through which the data is collected were to be improved then the mission objectives would also be improved.

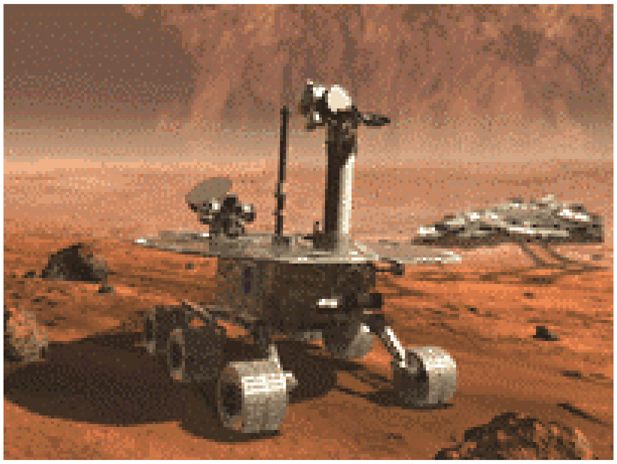

Figure 1: Wheeled Rover on Mars

APPROACH

One current area of research is to collect data and take pictures from the surface of Mars using semi-autonomous vehicles. The vehicles, both satellites and surface rovers, play a major role in the exploration of Mars. Although satellites are a good way of collecting data they will not be discussed in great detail. Instead, this paper will deal mainly with surface vehicles and associated technology in the exploration of Mars.

Mobility on Mars: Wheels vs. Legs

The Martian rovers that are currently in use are small and have wheels. They are not very difficult to power or control. The problem with wheeled vehicles is that they are inherently suited to flat ground and have limited degrees of freedom, thus limiting the amount of terrain that they can traverse and their usefulness to explore and collect data.

On Earth roads are relatively level, cleared and paved to accommodate vehicles with wheels. However, on Mars there are no paved or cleared roadways. The Martian surface is cluttered with rocks of various sizes that cause navigation problems for small, wheeled rovers. In order to navigate the Martian surface a rover must take a circuitous route to avoid large obstacles and prevent it from getting stuck. These maneuvers are both energy consuming and counter productive because of the downtime needed for frequent recharging of the energy source. Clearly, a vehicle more suited to the chaotic terrain on Mars is needed.

An ideal solution would be to design a vehicle that was autonomous, versatile and agile. The first step in developing such a vehicle is to examine real-life models, both natural and artificial. Terrestrial man-made vehicles are typically limited to smooth terrain; even tanks cannot negotiate large boulders. In contrast, insects use many small legs to navigate all types of terrain. The surface of Mars can be seen as very similar to the rocky soil on Earth from the perspective of a tiny millipede. Something as simple as this tiny

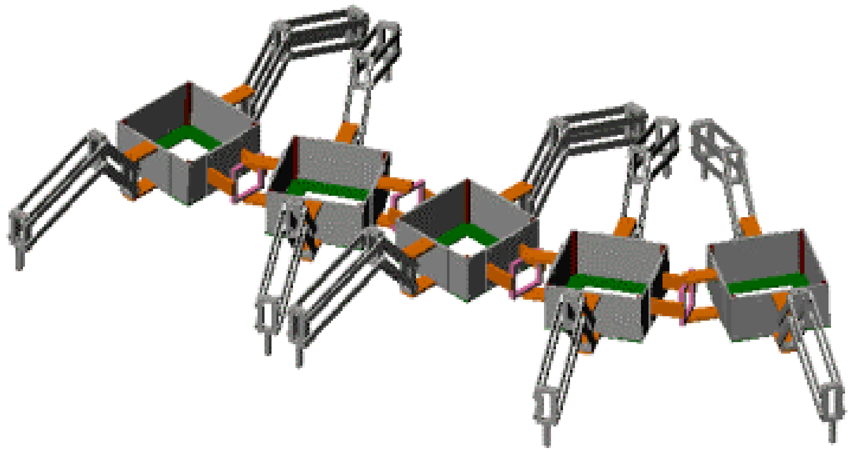

Figure 2: The MILLIPEDE

insect could be used on a larger scale as a model for a highly sophisticated walking mechanism.

There are several benefits to using a walking vehicle. As discussed earlier, the use of legs would allow the vehicle to traverse more difficult types of terrain. The walker would be able to step over obstacles that a normal wheeled vehicle would have to circumvent, thus making the line of travel more direct. This would save time and power for use in collecting data and samples.

Specialization vs. Modularity

Another important design consideration is the question of specialization versus modularity. Conventional surface exploration vehicles are limited to performing a few specific tasks such as mapping and specimen collection. Designing a *single* vehicle to accomplish all conceivable mission duties is clearly impractical; therefore, a module-based transportation system is needed to tackle the wide variety of possible tasks.

Currently, vehicles are constructed on a mission specific basis to perform certain experiments or tasks. The construction and design of these vehicles is very expensive and time-consuming. More ideally, a group of vehicles, or a single vehicle made up of many parts or modules, could perform a variety of tasks, thereby saving money and time.

Modular, walking vehicles, linked together like a millipede with each segment having a different operation to sustain the whole, could be made into any configuration necessary for a mission to Mars. This concept of a modular walker, or the MILLIPEDE, will be discussed in the next several sections.

RESULTS

Reason for Modularity

A modular walker design was chosen for several reasons. First, design and construction is much easier with a uniform module system. In other words, each module is the same, and can be fabricated easily and cost-effectively in mass production. This quick construction saves time and money in preparation for a mission.

Another reason modularity was chosen is that it allows for universal applications of the walker design. Modules can be used to fulfill power requirements, for collection and storage of materials, and for all types of scientific experiments. The modular unit was designed specifically for surveying and analysis of the Martian terrain. Therefore, the power and size constraints can accommodate various equipment and systems.

Built-in control and communication transceivers help make the walker an intelligent and powerful device. While in formation as a train of modular units, the walker can function as a multi-disciplinary device with one source of control, or “brain”. It can easily segment itself and still function as well as the original device, because each module is equipped with its own control system that is linked to other modules via communication ports and transceivers. This passive control system keeps one unit in control of the rest of the train until a segment detaches. The original control unit retains control of the other units that are still attached, while the detached segment enacts its own control system on one of its own units. This function has many potential advantages as shown in the following example: While in a train formation, one of the legs of the MILLIPEDE becomes lodged in between two rocks. The leg cannot be dislodged by the current configuration, so the train separates into several smaller trains of modular walkers. These walkers can continue on their original destination or assist the trapped walker from a more advantageous position.

Another feature of the control and communication system is that the units can relay information to each other. This not only helps the units work together, but also preserves any information that is obtained by a module that becomes non-functional during the mission. Combined with communication satellites, each unit can not only communicate

Modules

The solution to meeting changing needs in planetary exploration.

- Power Modules
  - Gather and provide power to the rest of the system
  - Allow for flexible power requirements and centralized generation systems
- Scientific Modules
  - University and industry sponsored projects and experiments can be easily implemented in one system.

with the others but also with Earth, sending data during missions and receiving new instructions.

Module Implementation

Power Modules

As discussed earlier, various types of modules are used in the walker. One that is absolutely necessary is a power module that not only stores and provides power, but is also rechargeable. Solar cells, or more specifically, photovoltaic cells, are used to transform energy from the sun into electrical power that is distributed throughout the system or stored in deep-cycling batteries for later use. This way, the walker can recharge during the day and still have power to run during the night. However, solar power alone has some drawbacks that will be discussed later. Alternative power sources can also be included in these power modules to provide more effective or efficient power.

Although the power modules act as the primary source of power for the walker, each module can be fitted with its own battery. This would allow each module to be independent of the others and of the power module, and would thus provide greater universality and redundancy. Another option available, which may be specific to certain module implementations, is the addition of a shallow-cycling battery for short bursts of high power. While most modules may not need this additional supply, it can be fitted in the module that needs it and be charged by the power module. Parallel arrangements of the power lines create redundancy in case of failure. Circuit breakers in each module also help protect other modules if one develops a short circuit.

Scientific Modules

A major reason for the modularity of the walker is in the wide range of functions that it must be able to serve. As mentioned earlier, creating one unit to do several tasks often becomes complicated and sacrifices the effectiveness of the unit. Also, once the unit serves its purpose it cannot be easily reused for other purposes. Therefore, a simple unit that could serve any number of functions is ideal. It is with this idea that the MILLIPEDE is geared towards its main purpose of scientific exploration and engineering measurements.

Current GPR systems are small and low power

One such example is surveying the surface of Mars. Modules with robotic arms are used for soil and rock collection. An opening in the bottom of the compartment allows for easy access to the surface. Mineral excavation is another useful implementation of a module. While a human could easily do these jobs, the walker allows for many more involved applications, such as sub-surface mapping. Microwaves transmitted into the surface of the planet reflect an "image" in a concept called Ground Penetrating Radar (GPR). Small machines about the size of a lawn mower and safe enough for a human to operate have been in use for some time on Earth. However, this procedure has never been attempted off-planet, and could provide a great deal of useful information for both scientists and engineers. Scientists could, in effect, peel away the surface layers of Mars, revealing the planet's history and life cycles. The same information could be interpreted to find safe landing and building areas, as well as mineral and water deposits below the surface. The advantage of the walker is quite evident in this application, as the walker would be able to cover vast areas and traverse all types of terrain. Through the use of several GPR units, given enough time, the walker could obtain a sub-surface map for the majority of the planet. This feature, combined with the Martian communication satellites (discussed later) would allow scientists on Earth to view the walker's mapping progress.

TECHNICAL ANALYSIS

Structural Design

The most fundamental component of the modular walker is the modular compartment, or cell. The cell is a box-shaped object designed to power, support and protect the drop-in mission module. The top of the cell is completely open, while the bottom has a smaller opening for easy access to the ground. All four walls are identical except for one feature: the two sidewalls that support the legs also protect the power channels in the cell.

As mentioned earlier, the power operates on two main busses; each is redundant and protected at each cell in case of failure or catastrophe. The power housing in each side of the module is supported with insulation and thicker walls to protect the module from interference and protect the cables from developing a short circuit. The mission modules themselves have protective housing on either the top or the bottom or both, so as not to restrain the design and function of the modules. For example, a particular mission module may only interact with the environment through the bottom of the cell. This module would have a protective shield on the top that locks into the cell, but the bottom would be open or have a "door" to open when the module is active.

On the exterior of the module are four universal joints: one on each side. On either the front or the rear of the module is a connecting joint that would allow the module to latch onto other cells. The opposite side has a receiving joint to establish connection. It is through these two joints, receiving and connecting, that the cells link up into a train of modular cells. While it has not yet been implemented, future design plans intend to make these connections powered, so that cells can interconnect and disconnect automatically. The other two faces with universal plates are used to support the legs. The leg joints are fixed into place after connection and are not designed to be removed during operation. The drop-in modules lock into place and receive power through at least one of two ports on the walls supporting the power busses.

Control Design

Aside from the power busses, there are also two control busses, or instrumentation lines, to control the walker. These redundant control busses run to the motor controllers in the legs and the control panels located within the module. Control is directly linked to communication, so commands and programmed instructions can easily be downloaded to the walker. Each control unit is capable of completely controlling the cell functions and mobility mechanisms. The module, however, operates independently of the control unit, but may work as an aid and even override the cell control in order to perform its intended function.

This control style is typical of the walker's passive control element. The system operates with several control units, but only one is active at a time. Each cell has a control unit. In a train made up of several of these cells, the units are prioritized so that only one is in control of the system at a time. Inactive control units may be used to run diagnostic checks to make sure the active control element is functioning properly. This ensures that the MILLIPEDE always operates under a fully functional control system.

Communication plays a very important role in the walker design and control system. Not only is each cell control unit outfitted with a transceiver, but the system is also designed to work with a communications satellite array orbiting the planet. These Martian satellites are used to locate the walkers via MGPS (Martian Global Positioning System) on the planet surface and transmit data between Mars and Earth. This way, not only can the information obtained by the robotic walker modules be uploaded to Earth as it is collected, but new commands and algorithms also can be downloaded to the same modules to correct problems mid-mission. Dual antenna arrays allow the cells to communicate with the satellites and each other at different carrier frequencies to prevent interference; high frequencies (cellular levels, approximately 900MHz) are used to communicate with the satellites, while lower frequencies are used to transmit between cells to increase range and reduce obstruction of the signal. This allows much more efficient communication in realistic situations, such as blackouts due to dust storms or obstruction of transmission in subsurface or covered regions.

The second purpose of the satellites is to locate the MILLIPEDE on the Martian surface. This is important for the cooperation of unit cells on tasks covering a large surface area

MGPS (Martian Global Positioning System)

The eyes and ears of the mission.

- Global Positioning System
  - The MGPS provides the MILLIPEDE with specific location data for surface and sub-surface mapping.

- The Mars – Earth Link
  - Doubling as communication satellites, the MGPS will allow NASA to relay information with the MILLIPEDE, such as new instructions or data retrieval.

and in applications of surface and sub-surface mapping. Modules intended for use of mapping terrain can apply a geographical location to the image and transmit the data to another computer to process the data. Also, units and trains can use this geographical location system to aid or link up with other "loner" or stray cells. The MGPS can be implemented in various effective ways with this universal system.

Detailed Design

Size and Shape of Unit Body

The body segments of the MILLIPEDE perform multiple functions. First, they support and protect the modules. Second, they connect and support the joints and legs. Finally, they house the slave leg controllers and decentralized power storage. Owing to these factors, much consideration was given to the body constraints.

Each modular cell is the same no matter what plug-in module is used. This allows for easy assembly, specific constraints for design of the module units, and easy manufacturing of the cell components. Second, the area allotted for the modular plug-in units is centered within each unit for better weight distribution. Since the cell not only connects to the legs but must also interface with at least two other units, an obvious and simple design for the modular body is a box. Third, the structure must be light and strong to support the weight of the loaded modules, legs and external forces.

The platform has a square design for simplicity and ease of manufacturing. Since all four sides are equal, one generic part can be replicated for use in all the side panels. To provide adequate volume while limiting size and weight, the unit cell is constrained to be half as tall as it is wide. This provides better balance as the center of gravity is better aligned in the middle of the cell. If the center of gravity were too high, the walker would have a tendency to tip over. Likewise, the body of the MILLIPEDE must be high enough off the ground to clear most obstacles.

The size of each body segment must be sufficient to allow modules of reasonable size to be transported while not so large as to consume excessive power. Considering the cost of transporting equipment to the Martian surface, a disproportionately large body segment would not return the expense of transport. Additionally, a larger body implies larger legs and connecting joints, both with reduced travel speeds and ground clearances. A miniscule walker would require miniature actuators and motors, which would increase the manufacturing cost of the

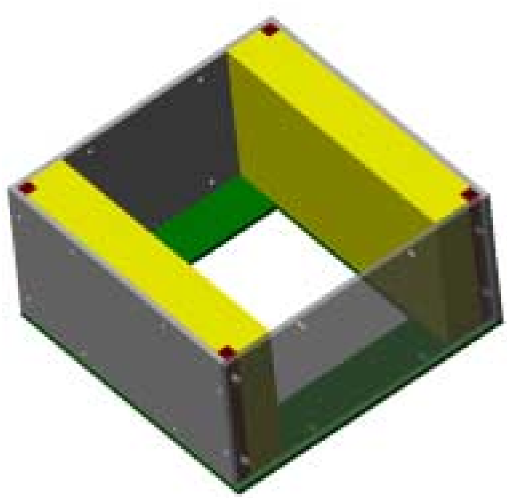

Figure 3: Body Cell of MILLIPEDE

MILLIPEDE. A smaller walker would also not be able to serve as many applications as a larger walker. We finally arrived at external dimensions of 12” wide by 12” long by 6” high. These dimensions best suit both the application and power requirements of the MILLIPEDE. The weight of each body segment plus the component module was approximated using the density of water to fill the volume of the modular cell. This approach yielded a weight of 32 pounds (in earth gravity) for each body segment. All materials for the body segment will be aluminum to maximize strength and manufacturability while minimizing weight and cost.

Other design features include a ¼” thick plate added to the bottom to provide stability and support for the component modules and corner bracing for joining the walls. Each wall has receptacles for leg, joint, or communication connections. Inside the walls are power, communication and control elements housed within the modular cell.

The remaining volume, a rectangular prism of 6” high by 8” wide by 11 ½ “ long, is reserved for the component modules. The bottom plate has an access hole in its center to accommodate various component module missions.

Leg Design

The surface of Mars is much like a rocky desert with many perilous obstacles. A vehicle must be able to move over this type of terrain with relative ease in order to successfully navigate the planet’s surface. The MILLIPEDE’s legs are very versatile and provide the necessary agility to conquer this dangerous terrain: the walker’s legs can spread out to keep the unit low and balanced, or it can stand tall to overcome large obstacles in its path. This versatility allows the MILLIPEDE to avoid obstacles by moving over and around them.

Each walker leg is made up of a body-leg adaptor plate, a hip, an upper leg, a knee, a lower leg, and a foot. The body-leg adaptor plate is identical to the body-body plate with the exception of shorter tabs. The hip is mounted on two pins and fits between the two tabs. The upper leg and lower leg are each made up of four members, connecting to the hip, knee, and foot via pin joints. Additionally, each upper leg and lower leg has an actuator attached, while the hip joint houses a servomotor.

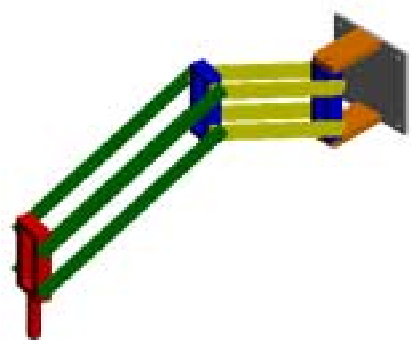

Figure 4: Basic Leg of MILLIPEDE

Each walker leg assembly has three degrees of freedom. The hip joint is mounted on two pins and controlled by a servomotor, allowing the leg assembly to rotate forward and backward, level to the ground. The upper leg and lower leg are each controlled by actuators. The motion of the upper leg and lower leg allows the foot to move up, down, towards the body, and away from the body by the combined efforts of the actuators. These three motions alone allow the walker to walk perfectly over a flat surface and avoid numerous obstacles over an imperfect surface.

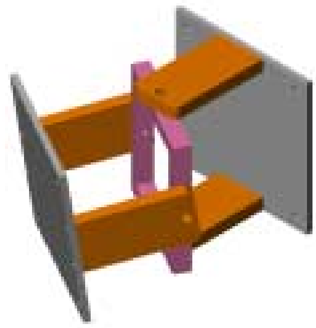

Figure 5: Body-Body Connection Joint

Power Systems

In order to determine the power requirements of the MILLIPEDE some preliminary calculations are necessary. The most important factor determining the required power is the weight of the body and mission modules. The maximum weight of a mission module can be estimated by assuming that the interior volume of the cell is filled with water. The interior volume of one cell is

$$11.5\text{''}\times 11.5\text{''}\times 6\text{''} = 793.5\,\text{in}^3 = 0.013\,\text{m}^3$$

The density of water is

$$\rho = 1000\,\text{kg}/\text{m}^3$$

So that the mission module mass is

$$\text{Mass: } m_{cell} = V \times \rho_{H_2O} = 13\text{ kg}$$

The empty mass of each cell (including body, legs and couplings) is 8 kg so that the maximum total cell mass is 21 kg. The weight of a cell is

$$F_{cell} = m_{cell} \times g_{Mars} = 21\text{ kg} \times 3.69\text{ m/s}^2 = 77.49\text{ N}$$

And the weight of a 3-cell segment is

$$F_{segment} = F_{cell} \times 3 = 232.5\text{ N}$$

Scaling this value by a safety factor of 2 yields a force per segment of

$$F_{segment} = 465\text{ N}$$

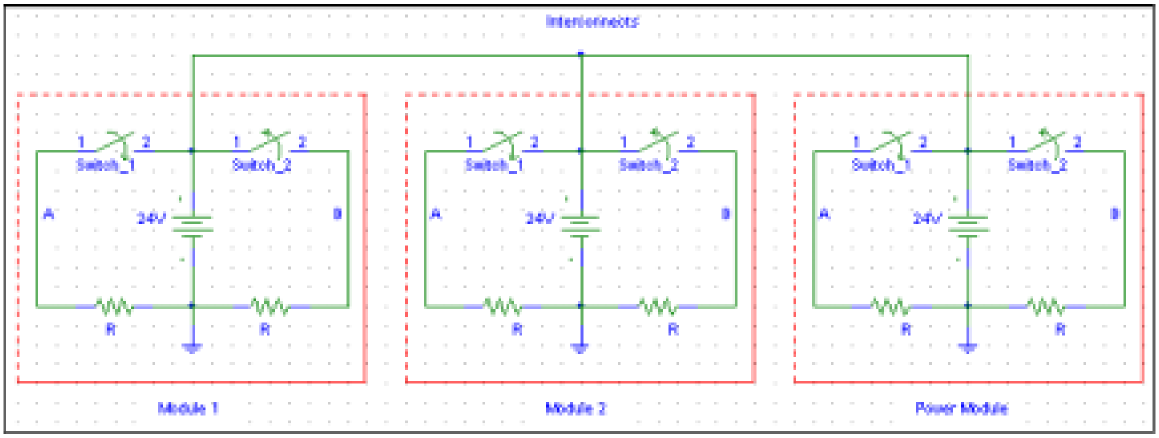

Figure 6: Simplified Module Power Schematic

Assuming that the MILLIPEDE travels at 0.1 m/s up a slope of 45°:

$$Power = F_{segment} \times v \times \cos(45°) = 465 \text{ N} \times 0.1 \text{ m/s} \times 0.707$$

$$Power = 32.9 \text{ W}.$$

The MILLIPEDE is designed to operate with a 24V power supply, thus the maximum current draw is 1.37 A or 228 mA per leg for six legs.

Since the MILLIPEDE's mission is long-term, the most ideal source of power is a rechargeable power supply. The existence of natural resources on Mars, what they are, and where they are found is not known at this time. This prohibits the possibility of using Martian resources as a power source for the MILLIPEDE.

While the dust storms on Mars can create wind gusts up to sixty-seven mph, the atmospheric density on the planet is merely sixteen thousandths of that of Earth. Thus, the Martian wind is also not a viable power source.

The only remaining feasible source of power on Mars is solar, although this technology also has drawbacks. The sun is farther from Mars than it is from Earth and thus provides less solar power. Frequent dust storms also limit the amount of power that can be derived from the sun's rays. However, even if dust storms create blackouts for the MILLIPEDE's system, the long-term benefits of solar power are overwhelmingly in favor of the technology. The question is whether solar power on Mars is suitable enough to provide power to the MILLIPEDE. As demonstrated below, solar energy is a sustainable power source for the Martian walker.

Assuming that a standard PV cell used in the following assembly provides 70mW/in^2, an average obtained on Marshall Brain's "How Stuff Works" web site. Each cell produces a set voltage as determined by its internal V/I characteristics. However, current is a different matter: the amount of current produced by the cell is directly related to the amount of energy absorbed by the panel. Discounting all other conditions, the solar irradiance, or the flux density of Mars is 489.2W/m^2, while on Earth it is 1367.6W/m^2. Therefore, the amount of energy hitting the surface of the Martian solar cell is approximately 0.431 times as much as the energy the solar cell would absorb on Earth. Therefore, we can assume that each PV cell on Mars would produce approximately 30.1mW.

Since the systems on the MILLIPEDE operate at 24V, a series of these solar panels must be assembled to provide this voltage. The power collected by the solar panels is then stored in deep-cycling batteries, which are typical in this type of application. Deep-cycling batteries will provide the MILLIPEDE with a long-lasting current supply and can be drained almost completely without harming the battery. Wiring the cells in series will sum the voltages in each solar cell. This 24-volt conglomeration is then referred to as a module. Modules hooked up in parallel will likewise sum the currents produced by each. Using the expected 30mW/in^2 PV cells, a solar panel of 9ft^2 will yield approximately 39-Watts. Since the system is expected to draw only 32 W in operation, the excess power generated can be stored in batteries to be used at night or during dust storms.

Figure 6 shows the parallel bus arrangement (A and B) with the circuit breakers represented as switches. Only one breaker is closed at a time during normal operation. Once the charge in the batteries, shown as 24V_{DC} supplies on the schematic, drop below a certain level, both breakers would open shutting down the walker and allowing the batteries to charge. These batteries would typically be of a rating of 30-amp-hours or more. At the peak-charging rate, it would take over 18 hours to charge a battery of this rating. Each resistor is representative of the load created by the motors used in the legs and the module's power requirements.

FUTURE RECOMMENDATIONS

There are several sections of the MILLIPEDE and its associated components that could not be implemented within the scope of this one semester project. Control and

Table 1: Mars / Earth Comparison

Parameters	Mars	Earth	Ratio (Mars/Earth)
Surface gravity (m/s^2)	3.69	9.78	0.377
Solar irradiance (W/m^2)	589.2	1367.6	0.431
Surface density (kg/m^3)	~ 0.020	1.217	0.016
Surface pressure (mb)	~ 6.1	1014	0.006

communication are based on a conceptual design and require much more practical and thorough design constraints. The MGPS would also require a great deal of research and testing. Control algorithms and implementation are also far beyond the scope of this project and should be handled by highly trained technicians.

As far as the MILLIPEDE is concerned, the largest remaining design problem is that of the interlocking joints between the segments. These joints allow the MILLIPEDE train to segment and reconnect for advantageous arrangements depending on the situation. Should the project continue, implementation of such a device is a necessity.

CONCLUSION

Rovers may be the traditional land vehicles used in previous space missions, but a new age has dawned and with it comes an evolution in technology. While a rover may be more power efficient than the MILLIPEDE, it certainly cannot compete with the agility of a modular walker. Nature has demonstrated that legs are ideal for conquering obstacles like the rocky deserts of Mars. Terrain aside, the MILLIPEDE can move in almost any direction or position, thus allowing it to do more on its own than any rover could possibly hope to accomplish.

As the voyage to reach the Martian frontier continues, a manned mission is just on the horizon. However, before Earth sends new explorers aimed at the Red Planet, all necessary precautions must be taken. The MILLIPEDE is a cost-effective solution to the problem of traversing the surface of Mars. By utilizing this autonomous robotic walker, information can be collected to ensure the safety of the future astronauts on Mars. Its modularity concept also creates a universality and boundless possibility that has not been seen before in any extraterrestrial mission.

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