



Lunar Wormbot

*Design and Development of a Ground Based Robotic Tunneling
Worm for Operation in Harsh Environments*



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1. Introduction

From 1969 to 1972, the National Aeronautics and Space Administration (NASA) sent Apollo missions to the moon to conduct various exploration experiments. A few of the missions were directed to the study and sampling of moon soil, otherwise known as lunar regolith. The extent of the sample acquisition was limited due to the astronauts' limited ability to penetrate the moon's surface to a depth greater than three meters. However, the samples obtained were sufficient enough to provide key information pertaining to lunar regolith material properties that would further assist in future exploration endeavors. Analysis of the collected samples showed that the properties of lunar regolith may lead to knowledge of processed materials that will be beneficial for future human exploration or colonization. However, almost 40 years after the last Apollo mission, limited information is known about regions underneath the moon's surface. Future lunar missions will require hardware that possesses the ability to burrow to greater depths in order to collect samples for subsequent analysis.

During the summer of 2010, a team (Dr. Jessica Gaskin, Michael Kuhlman, Blaze Sanders, and Lafe Zabowski) from the NASA Robotics Academy at Marshall Space Flight Center (MSFC) was given the task of designing a robot to function as a soil collection and analysis device. Working with the National Space Science and Technology Center (NSSTC), the team was able to propose an initial design, build a prototype, and test the various sub-systems of the prototype to be known as the "Lunar Wormbot" (LW). The NASA/NSSTC team then transferred the project to a University of Alabama in Huntsville (UAH) Mechanical and Aerospace Engineering (MAE) senior design class for further development. The UAH team was to utilize the NASA Systems Engineering Engine Design Process in the continuance of the Lunar Wormbot project. This process was implemented in order to coordinate the efforts of the team and guide the design of the project to ensure a high quality product that met requirements within the academic year timeframe.

When the transition from the NASA/NSSTC team to the UAH team occurred in August 2010, the scope and requirements were provided to the UAH team. The main objective for the UAH team was to design and fabricate a robotic burrowing prototype using peristaltic or earthworm-like motion with the purpose of collecting soil samples. The team was tasked with the design of a sub-system of the LW called the locomotive, or active, segment. Through the design process, the team extensively reviewed the requirements and functions to be performed of the LW, which led to the proposal of a final design. The present paper provides the details of the development of the design up to and including the Critical Design Review (CDR) of the Lunar Wormbot. This document briefly describes the overall system and its functions but primarily focuses on the design and implementation of the locomotive segment. Content presented includes: general design and system functionality, technical drawings, system analysis, manufacturing methods, and general project costs.

2. Purpose

The purpose of this LW project is to develop an innovative system to enhance current planetary exploration objectives. Specifically, the presented system will be considered effective if it is capable of acquiring subsurface soil specimens in harsh environments. This ability may provide valuable information for future In-Situ Resource Utilization (ISRU). Additionally, the proposed system is designed to eliminate human interaction- thus enabling astronauts to focus on higher level tasks. The following is the mission statement of the UAH team:

Mission Statement

The program goal is to lead to knowledge enabling a burrowing robot to operate on the lunar surface to gather soil samples. Leading to that goal, and staying within the scope of the time period of this project, a single, prototype LW will be produced for earth based testing by the UAH team. This robot will be considered successful in its mission if it offers the ability to burrow through a fine particulate soil simulat, return testing data leading to improvements in design, and exhibits the robustness necessary for space based soil sampling.

3. Activity Plan

Organization of team structure was a critical task in the early stages of the project. Through the initial stages up to the preliminary design, the project tasks consisted of 7 major subjects shown in Figure 3.1. Team members were assigned as subject leaders in which the timely completion of the subject was the individual's responsibility. After the preliminary phase completion, the team decided to implement an alternative structure. The team concluded that the most efficient means of achieving success was to assign tasks to the team members most interested and capable of performing the task. This structure increased individual accountability specific to unique tasks instead of a broad project area. Tasks were discussed and assigned during regular weekly meetings. The team member responsibilities are listed in detail in the Gantt chart in Figure 3.1 for the preliminary design phase and in Figure 3.2 for the final design and fabrication phase.

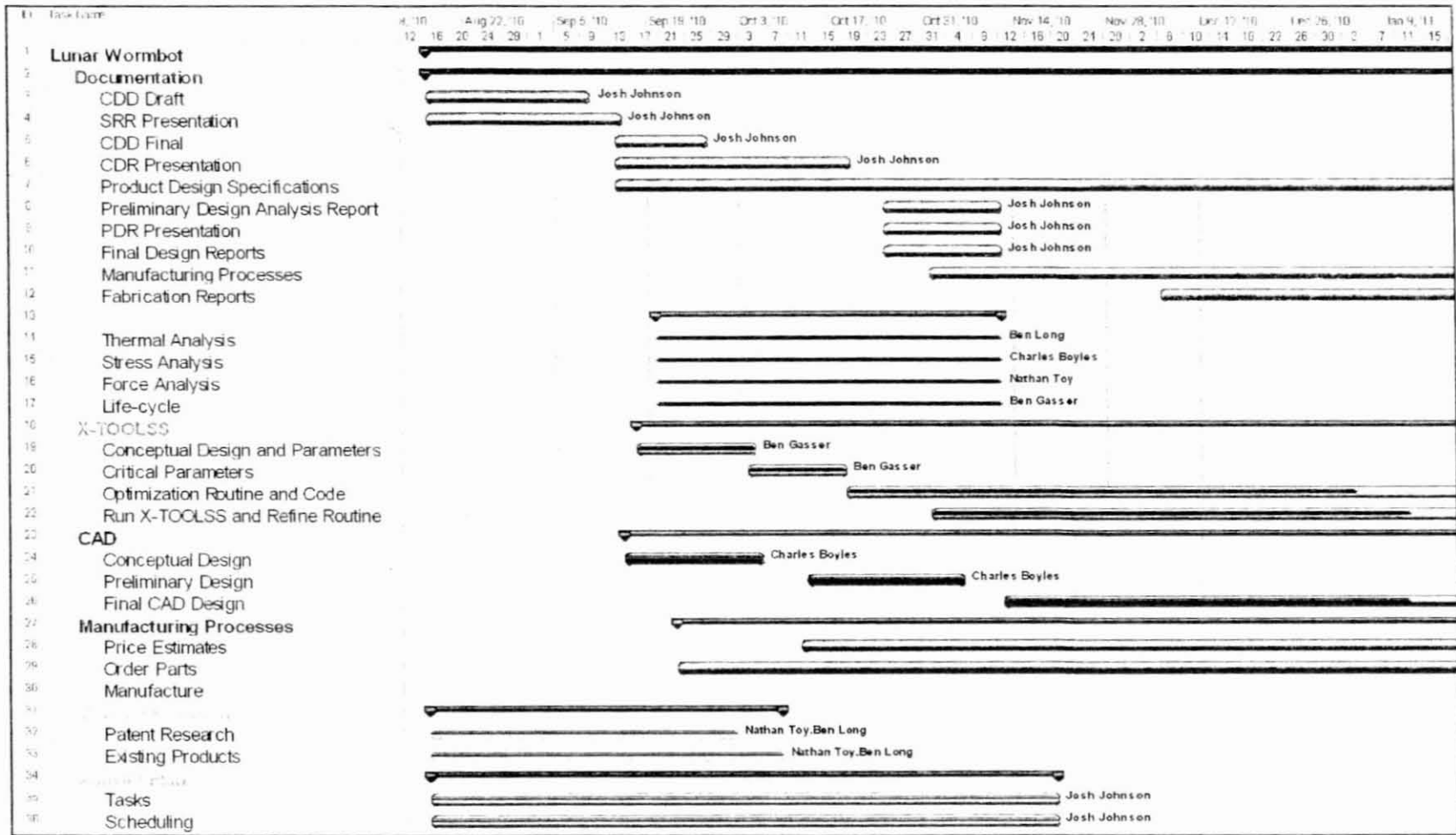


Figure 3.1: Conceptual and preliminary design phase tasks

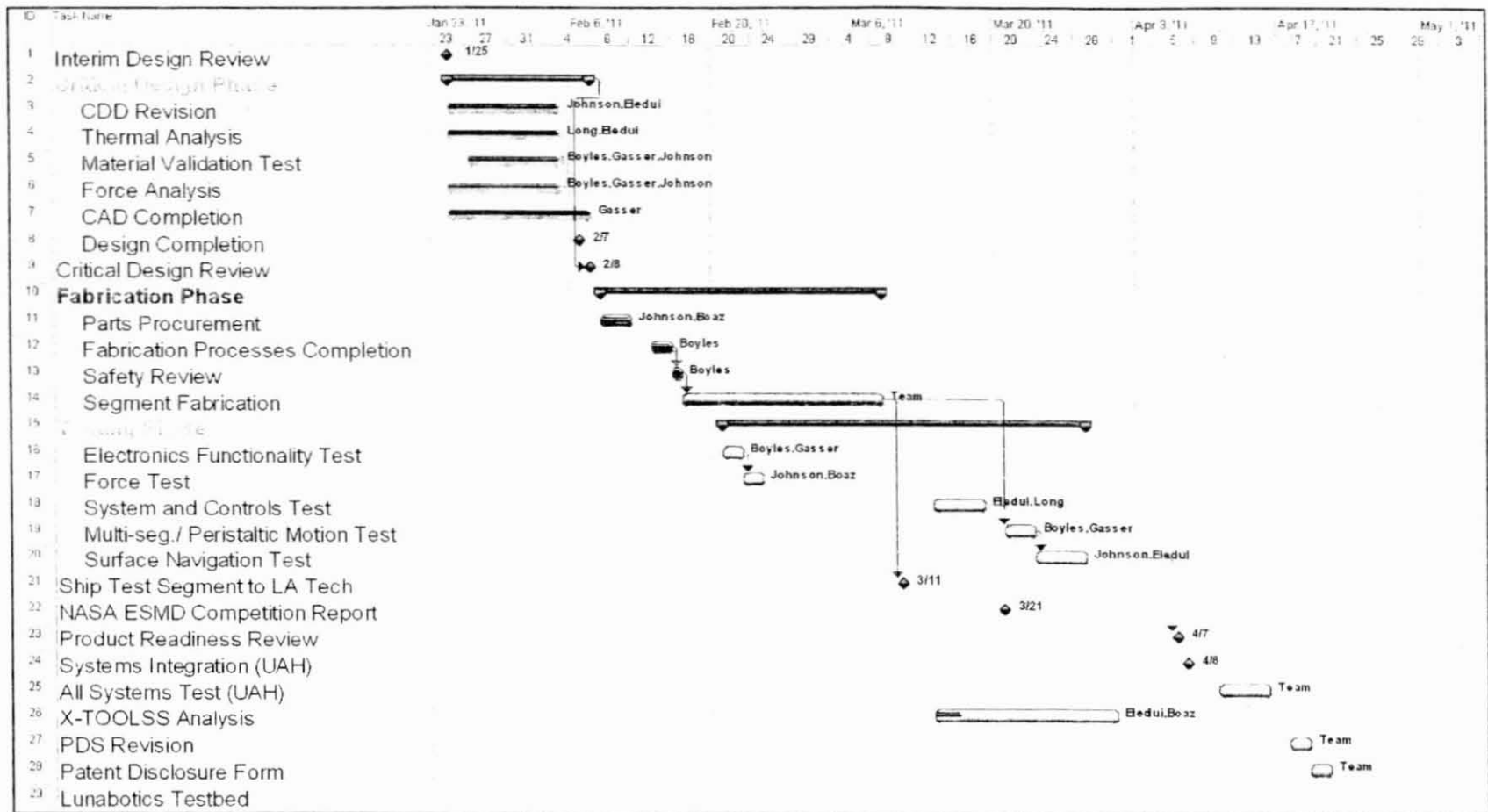


Figure 3.2: Final design and fabrication phase tasks

4. Major Design Reviews

A primary objective of the UAH team was to utilize the NASA Systems Engineering Handbook and implement the NASA Systems Engineering Engine. Shown below in Figure 4.1 is the Systems Engineering Engine used by NASA and as a guide for the Lunar Wormbot Project. Following the handbook's guidelines, the team presented several design reviews for the customers and locally interested professionals. The reviews conducted to date include the following: System Requirements Review (SRR), Conceptual Design Review (ConDR), Preliminary Design Review (PDR), and Critical Design Review (CDR). The purpose of the SRR was to establish the mission requirements, confirm performance requirements, and establish feasibility of the cost and design. The ConDR and PDR were presented to establish that the conceptual design met the technical requirements and that the design could be produced with acceptable risks and feasible costs. The purpose of the CDR was to assess the detail design configuration documentation, provide technical analyses, and present verification test results. The PDR and CDR were presented to the Thermal and Mechanical Analysis Branch at MSFC.

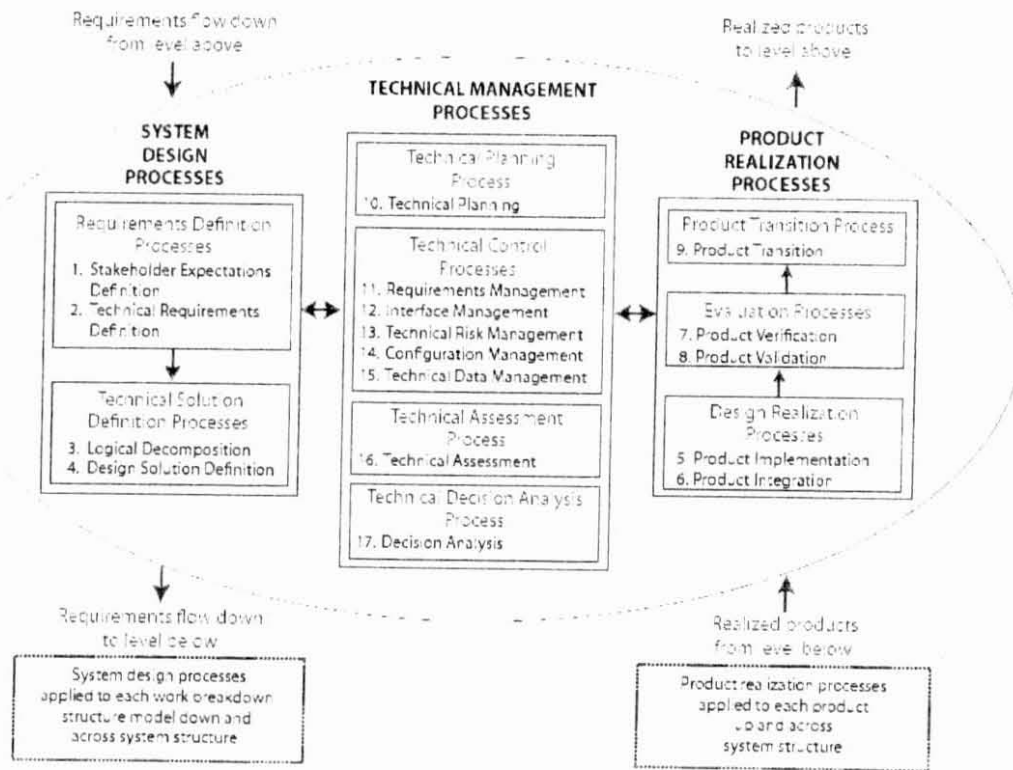


Figure 4.1: The NASA systems engineering engine

5. Conceptual Design

The initial LW design concept was provided by the NSSTC team. The UAH team was briefed with general requirements for the mission. Research was completed to determine the inherent difficulties involved with working on the lunar surface and to understand the fundamental physics of the project. A thorough patent search was conducted to examine similar products already in existence. With a basic understanding of the physical requirements, the team produced several variants of the original concept.

5.1. Project Requirements/ Concept Description Document

The primary purpose of the Concept Description Document (CDD) is to provide the requirements for the mission. The project requirements definition was a collaborative effort between the UAH team and the customers. These requirements were decided upon based on many factors including the time constraint of the project, the available budget, and the scope of the mission. It was determined that under the time constraints of the project, the team would focus primarily on the design, manufacturing, and testing of the active body segments. The logarithmic conical auger and ultrasonic drill bit as well as the sampling segments were to be developed by Louisiana Technical University (LA Tech). Due to the cost of materials necessary to operate on a lunar surface, it was also decided that the prototype would be limited to operating in earth conditions while keeping in mind future adaptations for space and commercial operations. Refer to Appendix A for the complete CDD documentation.

The major requirements of the project listed in the CDD are as follows:

- The LW shall be capable of burrowing through fine particulate matter.
- The LW shall implement peristaltic locomotion allowing one-dimensional burrowing, and should have segments articulated in three dimensions.
- The LW concept shall be designed for Earth based testing.
- The LW shall be capable of acquiring 50 one gram samples at various depths.
- The LW shall be capable of utilizing a power source supplying no more than 20 Watts peak power per segment.
- The LW shall use an elastic, water-tight skin material capable of insulating internal electrical and mechanical systems from fine particulate matter.
- The LW shall have space to integrate a sensing and navigation package.
- The LW design shall be analyzed using modeling and simulation techniques prior to prototype testing.
- The LW shall produce at least 66 N of force directed perpendicular to the segment's longitudinal axis at the center hinge.

5.2. Patent Search

A patent search is critical in the conceptual design phase for several reasons. A patent search helps to ensure that other designer's intellectual property is not infringed upon during the design process. Another reason to conduct a patent search is to view existing concepts for design ideas or ways to significantly improve the concepts considered.

Forty-four patents detailing the designs of earth and space burrowing robots were researched. Most of the patented devices researched utilized hydraulic or impact actuation as a burrowing mechanism, however none of the patented devices utilized the required peristaltic locomotion. Though many patents were reviewed none were found to be significantly relevant or similar to the present project.

5.3. Benchmarking

Forty-four patents for boring implements were reviewed in depth. While no patented machines were influential, some experimental devices shared common features with the NSSTC's original LW design. As this is a novel design in development, a lack of patentable work prior to this project is to be expected. An experimental device (Figure 5.3.1), developed by Chuo University in Japan, utilizes several mechanical functions desired by the Lunar Wormbot team. This device utilizes a flexible wall and its motion is driven by servo motors. It is capable of changing its diameter while undergoing general peristaltic motion. This device is capable of being sealed from lunar regolith, but does not apply force loadings required to compact soil.

The Lunar Wormbot will, however, carry and make use of an ultrasonic drill similar to the one described in US patent number 6863136 (Figure 5.3.2). The ultrasonic drill has proven very useful for coring and removing cylindrical sections of hard, brittle material in laboratory tests. This device will be used to core and split large ejecta obstructing the LW's path in addition to its utility in sampling (Bar-Cohen Et al). This implement requires a very low preload force, 10 Newtons, and is capable of coring glassy mineral formations.

5.4. Research

The team researched various properties of lunar soils, and specifically lunar regolith. In addition, the team studied peristaltic motion in natural settings as well as in mechanized implements. It was determined that organisms which undergo peristaltic motion do so by expanding their diameters while constricting their lengths in sequential fashion (Ilmenau). The team is under the direction of the customer representative, Blaze Sanders, who has experience in robotics. Mr. Sanders has been involved with the project since the summer of 2010, and is the point of contact between the team and the NSSTC.

Apollo program research details the particulate composition of the regolith, as well as probable compaction details. According to Carrier, soil samples taken from Apollo 15 near Hadley Rille indicate compaction greater than ninety percent at one meter below the surface. From collected sample data, Figure 5.4, half of all soil material recovered passed through screens 0.1mm in diameter, and ten percent of material recovered passed through screens 0.01mm in diameter ("Particle Size Distribution of Lunar Soil"). The regolith layer extends roughly ten meters below the surface, followed by large scale ejecta (Hörz et al).



Figure 5.3.1: Chuo University's wormbot

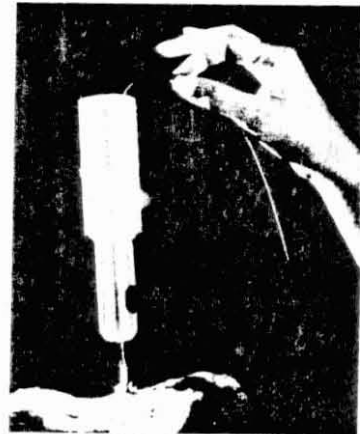


Figure 5.3.2: Ultrasonic drill
US patent number 6863136

The size, shape, and chemistry of lunar regolith vary with topology, with deeper areas of regolith near crater banks, and shallower areas near craterless void areas. Generally, regolith is composed of non-spherical glassed minerals (Hörz et al). The absence of atmosphere results in continual bombardment with solar radiation, charging particles on the lunar surface. The charging of particles causes them to be attracted to any non-like charged body; hence it may be possible to repel electrostatically charged lunar dust, or intentionally collect electrostatically charged dust (O'Brien).

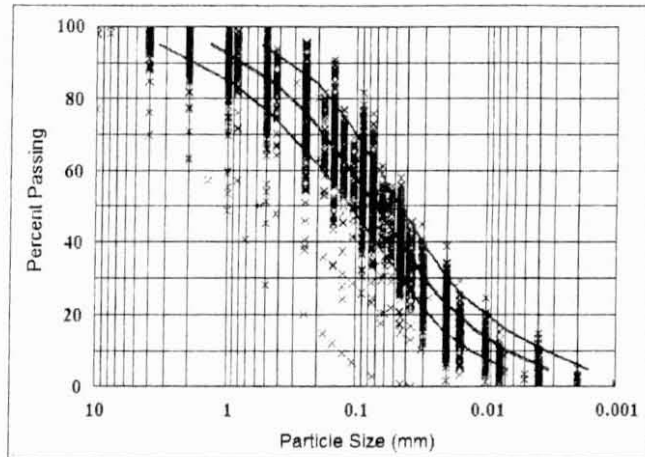


Figure 5.4: Lunar particle size (Carrier, 2005)

5.5. Conceptualization

During the design phase, several locomotive segment concepts were considered and analyzed. One specific concept, Concept # 1, was provided to the team by NASA and the NSSTC. Concept # 1, shown below in Figure 5.5.1 below, uses four AX-12 servo motors per segment to spin a three bar linkage which pushes on the sidewall causing it to expand outward. A clearer view of the servo motors and three bar linkage can be seen in Figure 5.5.2 on the following page. As a section collapses, the sidewalls press outward to grip the wall of the burrowed tunnel, allowing other sections to expand and move further along the tunnel. This is the basis of the concept's peristaltic motion design.

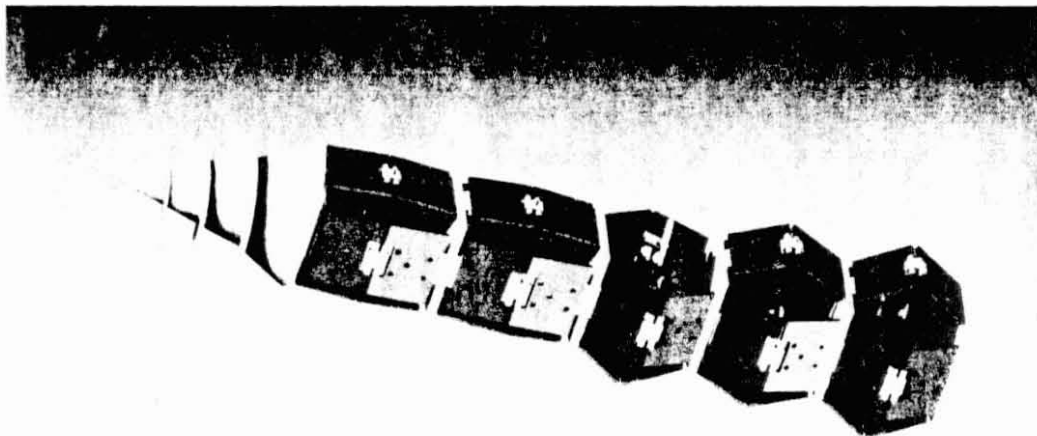


Figure 5.5.1: Concept #1: NSSTC AX-12 design (rigid wall)



Figure 5.5.2: Concept #1: AX-12 model interior

From the NSSTC's original design, the UAH design team produced a variant of the design, Concept # 2, shown below in Figure 5.5.3. This concept is identical to the original NSSTC's design with the only exception being the use of the linear actuators in place of the AX-12 servo motors. The benefit of this concept compared to the original is Concept # 2 was less complex, more powerful, and had fewer failure modes due to fewer moving parts.



Figure 5.5.3: Concept #2: Interior view of linear actuator design

The third and fourth concepts considered by the UAH team share the same basic internal structure, as shown in Figure 5.5.4 and Figure 5.5.5. Both concepts make use of three linear actuators per segment. These actuators share an equal radius from the center of the bulkheads. As the actuators compress, a wall material pushes outward, providing a normal force between the LW and the burrowed tunnel wall, allowing for peristaltic motion. The main difference between Concept # 3 and Concept # 4 is that one uses a flexible wall which is pressurized internally, and the other uses a spring wall. The flexible wall, Concept # 3, would have required the LW to be fed a consumable gas from an above surface support structure via a tether. The spring wall concept, Concept # 4, uses a material capable of elastic deformation as the linear actuators compress. Also, Concept # 4 utilizes a leather skin to cover sheathe the entire locomotive segments. The leather is used to prevent any particulate intrusion that may lead to mechanical failure.



Figure 5.5.4: Linear actuators about endplate

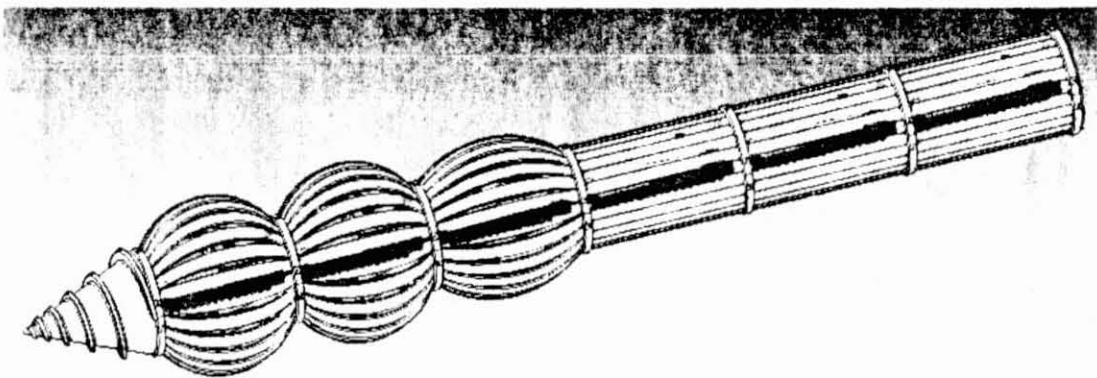


Figure 5.5.5: General configuration of Concept # 3 and Concept # 4

After carefully analyzing the aforementioned concepts, the UAH team decided to pursue the development of the spring wall concept, Concept # 4. This concept provides an advantage in many areas over the other three concepts. The spring wall design allows for a smaller cross section than the first two designs. This is because the design relies on a circular cross section, rather than a square one. With less cross sectional area and the lack of rigid, metal side walls and hinges, this concept would require less mass. The mass parameter is important due to its proportionality to cost in the area of space transportation. Although the choice of spring wall used in this design can be complex to analyze, the base structure is less complex, which will lead to fewer failure modes. Having three actuators per segment, each capable of independent movement, allows for three dimensional movement – an ability not found in the original design.

These four concepts were introduced into an evaluation matrix (Table 5.5.1) in order to determine the best possible design with respect to key parameters. First, the team listed all criteria that each concept would be subject to. These criteria were given a weight and then rated on a scale from one to four with one being the least desirable and four being the most desirable option. The weight and rating of each option was based on team discussion, educated assumptions, and preliminary technical analysis. For example, the weight for Concept # 1 is less desirable than the weight of Concept # 4 due to fewer parts and smaller cross sectional area. The weighting of the criteria yielded the most important parameters of volume, power consumption, skin and wall complexity, and the failure modes predicted to occur in each design. The power consumption parameter shows that Concept # 2 would be most efficient due to the fact that there are less moving components and the linear actuators position allows 100% efficiency to the rigid side walls. Concepts # 3-4 would use more power due to a lower efficiency in side wall force because of the axially mounted actuators. The evaluation of failure modes resulted in the Concept # 4 being least susceptible to fail. Concept # 1 is the lowest rated due to the numerous moving parts and interfaces and possible skin failure from the sharp plate side walls or pinch points. Concept # 2 was rated slightly higher primarily because the implementation of the linear actuators decreased the amount of components. Concept # 3 also required fewer components but the use of consumables resulted in the same rating as the previous concept. After evaluation, Concept # 4 was least likely to fail due to fewer components and no consumable usage. Other various parameters such as three-dimensional motion, a secondary goal of the project, were evaluated to determine the best concept for design. Final calculations of the evaluation matrix resulted in the spring wall design, Concept # 4, being chosen.

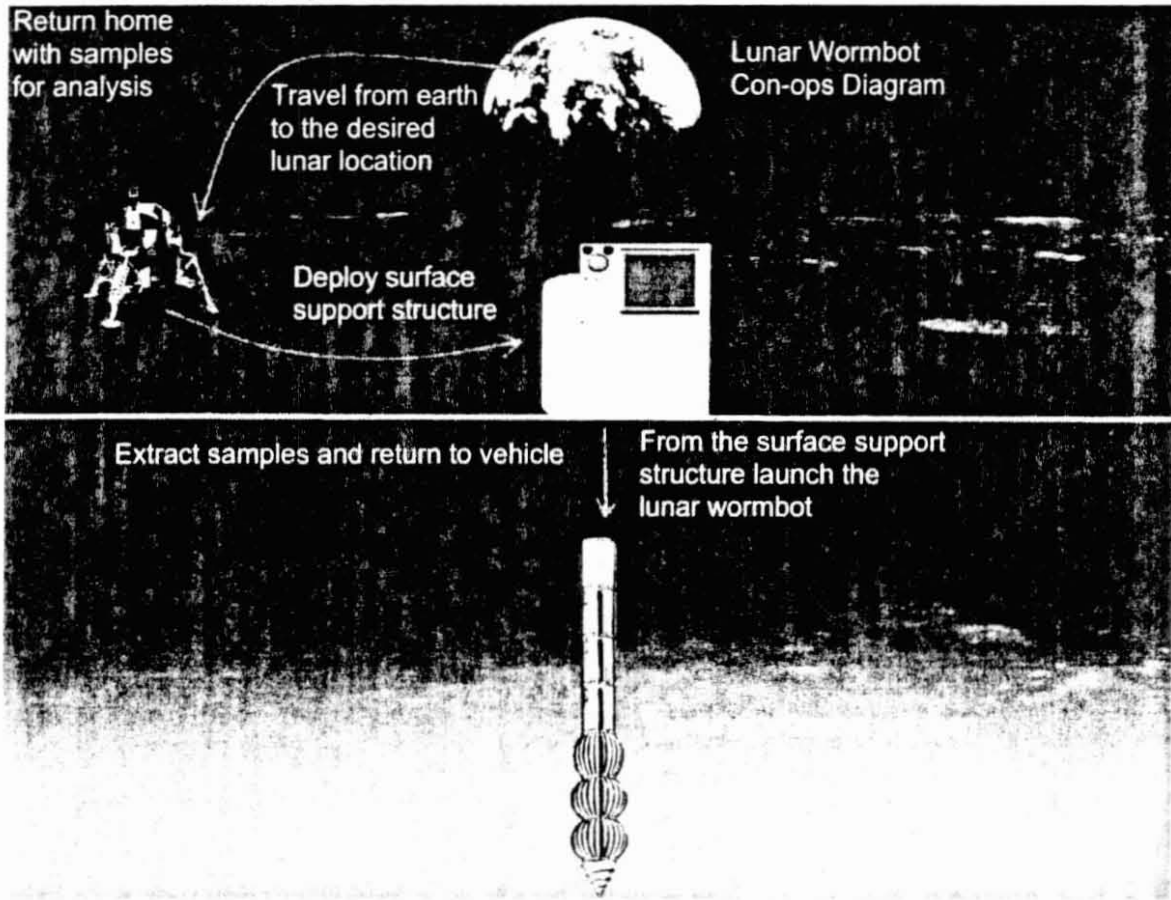
Table 5.5.1: Locomotive segment concept evaluation matrix

Body Evaluation	Mandatory (Y=1/N=0)	Weight	Scale	AX-12 (Rigid Wall)	Linear Actuators (Rigid Wall)	Flexible Wall w/ Pressurization	Spring Wall
Cost	0	9	4= Least Cost 1=Greatest Cost	2	3	3	4
Movement Simplicity	0	6	4= Simplest 1=Most Complex	1	2	2	4
Flexibility (3-D Mechanical Movement)	0	5	4= Most Flexibility 1=Least Flexibility	1	1	3	4
Regolith Resiliency	1	10	4= Most Resilient 1=Least Resilient	1	1	4	.3
Skin Complexity	1	10	4= Least Complex 1=Most Complex	3	3	1	2
Volume	0	10	4=Smallest Volume 1=Largest Volume	1	1	3	3
Weight	0	8	4=Lightest 1=Heaviest	1	2	3	3
Technology Readiness	0	4	4=Most Ready 1=Least Ready	4	3	2	2
Power Consumption Less Than 20 W	1	10	4=Lowest Power Consumption 1=Highest Power Consumption	3	4	3	3
Safety	0	4	4=Most Safe 1=Least Safe	1	2	2	4
Critical Failure Modes	0	10	4=Least Susceptible 1=Most Susceptible	1	2	2	3
Utilizes Peristaltic Motion	1	2	4=Most Peristaltic 1=Least Peristaltic	2	2	3	4
Utilizes Consumable Mass	0	5	4=No Mass Consumption 1=Large Mass Consumption	4	4	1	4
Recycleable	0	7	4=Most Recycleable 1=Least Recycleable	2	2	1	2
Ease of Maintenance	0	9	4=Easily Serviced 1=Difficult Service	1	2	2	3
Score		100.0%		44.5%	56.4%	59.6%	77.3%

6. Preliminary Design

The conceptual design phase determined the feasibility of various proposed concepts in which one design prevailed. The preliminary design, however, was composed of three main tasks to which the prevailing design was subjected. These tasks provided the product architecture, the configuration design of the parts and components, and the parametric design of the parts and components. The following sections capture the details of the preliminary design phase in which the LW segment design was engineered.

6.1. Concept of Operations



6.2. Design Concept

The design concept chosen uses electronic linear actuators and a composite spring wall to accomplish peristaltic motion. The design utilizes eight identical locomotive segments in which the active segment has three major sub-systems: linear actuators, composite side walls, and electronics. Other components include bulkheads, protective skin, mounting brackets, mounting bolts, and wiring bus conduit. The electronic linear actuators with internal potentiometers are bolted into the aluminum bulkheads. There are approximately twenty-five fiberglass wall strips that are snap-fit into the aluminum bulkheads. The protective layer to be applied is approximately one-eighth inch thick. A plastic wiring bus conduit is clamped to the center of the two bulkheads in the lateral axis of the segment. The system hierarchy can be seen on the following page in Figure 6.2.1.

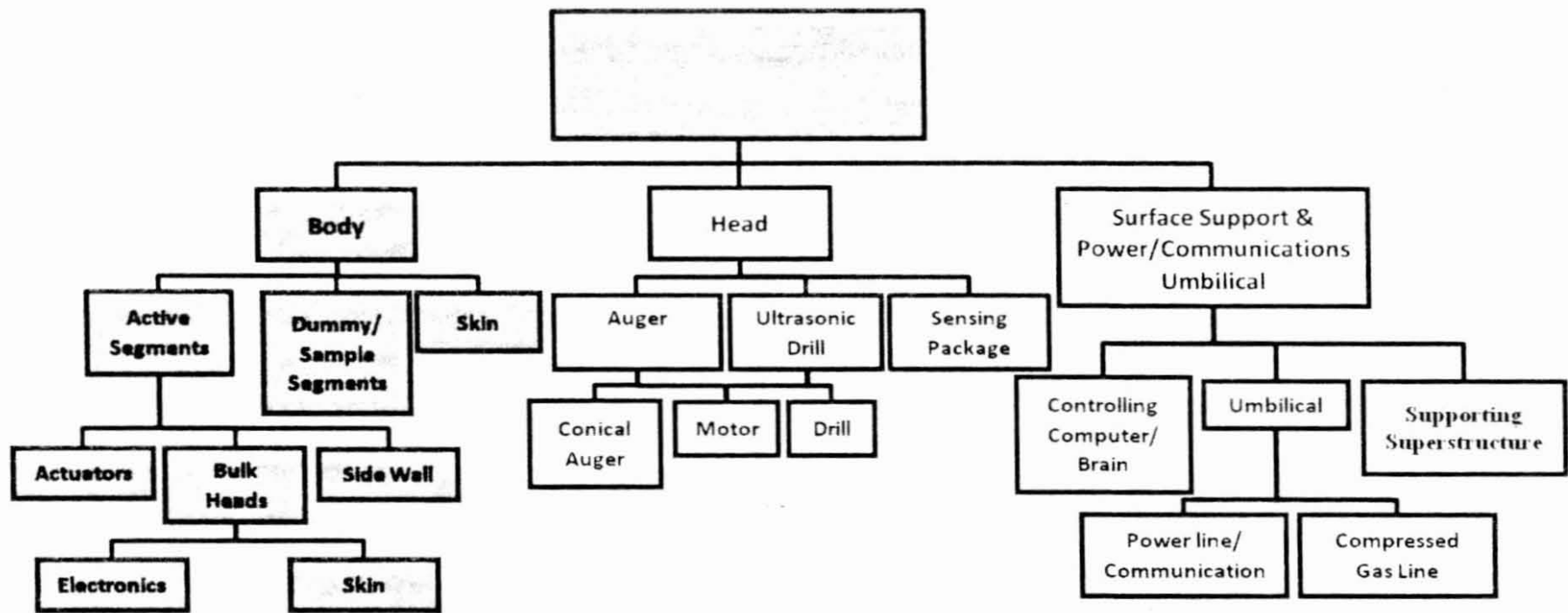


Figure 6.2.1: System hierarchy

6.3. Material Analysis

The materials which make up the Lunar Wormbot must be able to withstand the large temperature difference experienced on the moon. However, the initial prototype used for earth based testing need only withstand the temperatures experienced on earth. Earth based operation conditions are assumed to be from 40-90°F. Relevant material properties are included in Table 6.3.1.

Table 6.3.1: Lunar Wormbot Materials

Material	Location	Modulus of Elasticity (Mpsi)	Thermal Conductivity (W/m ² K)	Ultimate Strength(ksi)	Yield Strength(ksi)
Fiberglass	Sidewall	11.5	1.3	500	—
Leather	Skin	—	0.14	—	—
Plastic	Actuator	—	—	—	—
Copper	Wiring	16	401	49.9	48.3

The critical property for the aluminum bulkheads is strength since they are the primary support structure for the LW. Therefore, the aluminum must have the strength to maintain the LW's shape and thus its ability to function. The fiberglass must have strength to be able to transfer the linear force of the actuators into lateral force through column buckling. In addition to strength, the fiberglass sidewalls must have the flexibility to undergo the cyclic loadings necessary for peristaltic motion. One of the major concerns for the leather skin is how easily it will transfer heat to and from the LW and its surroundings. A similar situation occurs with the conduit, between the wiring and the LW's body. The copper wiring's thermal conductivity is important because the wires will be connected to the surface support structure and therefore will act as good conductors by transferring heat from the LW to the surface.

6.3.1. Corrosion Relevant to Design

This design is most likely susceptible to crevice and galvanic corrosion. Crevice corrosion may occur around the interface of the bulkhead and mounting brackets. Since the bulkhead is made of aluminum and the mounting brackets are made of steel, galvanic corrosion could accelerate the overall degradation of the materials. In this case, steel acts as a cathode while the aluminum acts as an anode.

6.3.2. Fatigue

The composite sidewalls will be the most likely component to fail due to cyclic loading. However the sidewalls are projected to sustain the cyclic loadings for the required lifetime of the Lunar Wormbot, which is one voyage to a depth of 15m and back. Future tests will be run to observe the effects of cyclic loading on the composite sidewalls.

6.4. Technical Analysis

6.4.1. Finite Element Analysis

One type of technical analysis performed on this system was Finite Element Analysis. This analysis focused on the performance of the bulk heads to determine the necessary thickness to withstand the loads and to identify areas in the bulk head where weight could be removed. This analysis was performed using PATRAN/NASTRAN. The bulk head is constrained along the outside edge and three loads of two hundred Newtons each were applied. These loads were chosen based on the maximum output of the linear actuators. Below are the results for the stress (Figure 6.4.1.1) and the deflection (Figure 6.4.1.2).

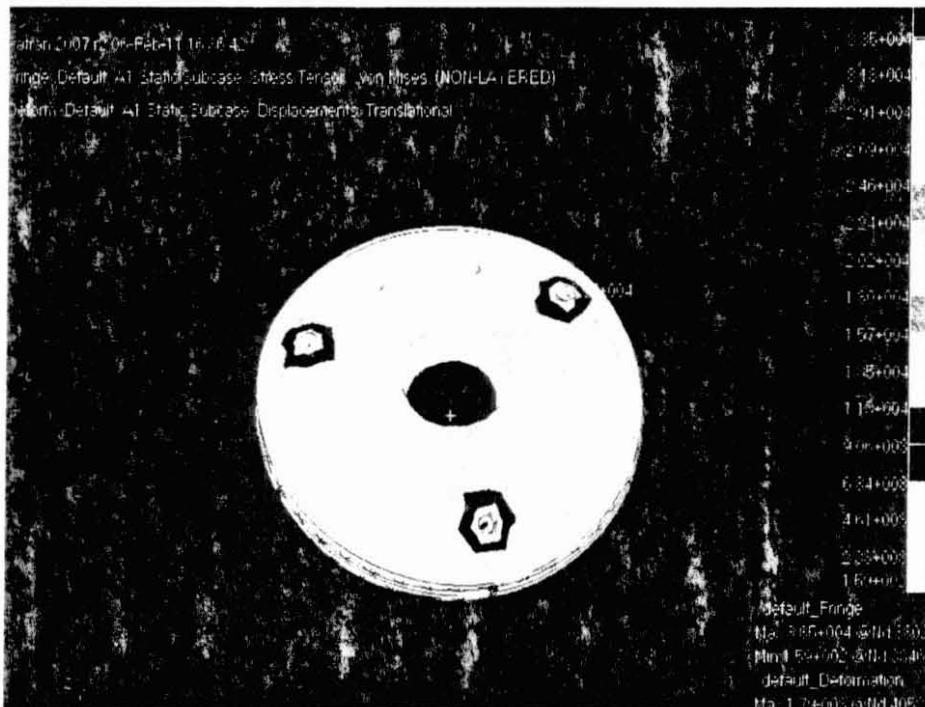


Figure 6.4.1.1: Stress Tensor

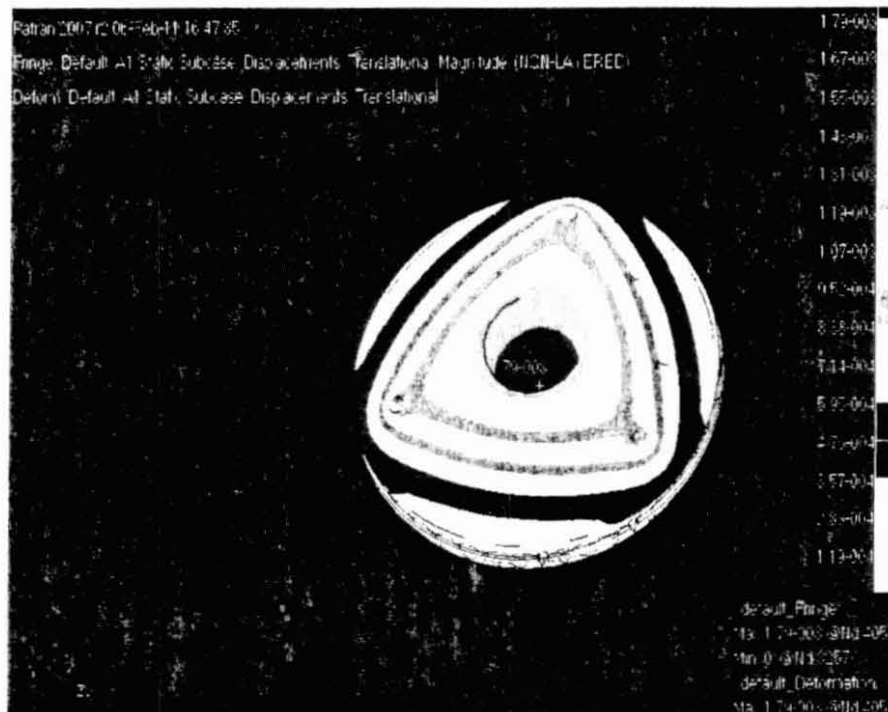


Figure 6.4.1.2: Deflection of bulkhead

From this analysis, it was determined that the maximum stress experienced by the bulk head is 3.35×10^4 psi, and the max deflection is 1.79×10^{-3} in. This yields a factor of safety of 298 which is extremely high; this has not been optimized yet because of the projects nature. Since the prototype is being utilized for Earth based testing only weight reduction isn't mission critical. For future space application, the bulk heads may need further optimization to reduce weight and allow for further electrical component attachment.

6.4.2. Thermal Stress Analysis

Because of the large temperature range experience on the lunar surface, a major concern was the thermal expansion experience by the aluminum bulkheads and the steel bolts. Due to the materials' different coefficients of thermal expansion (CTE) it was necessary to determine if the expansion of the aluminum bulkheads would create enough stress to cause the bolts to fail by stripping or shearing.

The CTE for steel and aluminum are respectively, 17.6, and 24.3 ($10^{-6}/K$). The bolts were modeled as through bolts with a nut on the other end. The force in the bolt created by the difference in expanding materials was added to the preloaded force experienced by the bolt. This total force was then compared to the force required to strip the bolt and its minimum tensile strength. It was concluded that given a temperature difference of 356°F there would not be enough stress in the bolt to cause a failure. The results can be seen below in table 6.4.2.1. For the detail analysis reference Appendix B for the Mathead file.

Table 6.4.2.1: Forces in Bolt (lbf)		
Total Force in Bolt	Required Force for Stripping	Required Force for Shearing
1018		

6.4.3. Thermal Analysis: Heat Dissipation

A thermal analysis was conducted to ensure that internal temperatures of the LW would remain at a safe working level for the structural materials and electronics enclosed within the segments. Calculations to achieve a good approximation of the internal temperature were performed in Mathcad version 15. Basic equations for this analysis were taken from "Fundamentals of Heat and Mass Transfer" Sixth Edition, by Incropera, Dewitt, Bergman, and Lavine.

Some broad assumptions were made to simplify this analysis. A general understanding of the approximate temperature ranges was sufficient rather than knowledge of exact temperatures. For this analysis, steady state heat transfer and a uniform internal temperature distribution were assumed for simplicity of analysis. It was also assumed that the peak power of 7.147 Watts was the only significant source of heat, and that those 7.147 Watts were converted into heat energy at fifteen percent efficiency. This allowed the team to analyze a "worst case" scenario to observe what the highest temperature ranges encountered could be.

Two mediums were analyzed, sand and lunar regolith simulant, as possible test mediums for the LW to burrow through. The sand and lunar regolith simulant were analyzed at standard sea level conditions. The following equations from "Fundamentals of Heat and Mass Transfer" were used for this analysis.

(1) $S = \frac{2\pi L}{\ln(4L/D)}$ From table 4.1, pg. 209, shape factor for a vertical cylinder in a semi-infinite medium.

(2) $q = Sk(T_s - T_{inf})$ From table 4.1, pg. 209, heat transfer by conduction using a shape factor.

(3) $q = \frac{2\pi Lk(T_i - T_s)}{\ln(r_2/r_1)}$ From equation 3.27, pg. 117, heat transfer by radial conduction through a cylindrical wall.

With known dimensions for length (L) and diameter (D) of an individual segment, a shape factor (S) was calculated in equation 1. Using fifteen percent of 7.147 watts for the transferrable heat (q), standard temperature (Tinf), and thermal conductivity of the test medium (k), the surface temperature (Ts) of the LW was calculated from equation 2. Finally, equation 3 was solved for the internal temperature (Ti) using known length (L), thermal conductivity, surface temperature of the LW (Ts), and internal and external radii (r1, r2).

The results, shown in Table 6.4.3.1, indicate the maximum internal temperature of the LW in each test material. Table 6.4.3.2 provides the maximum allowable temperatures of each component of an individual LW segment. By comparing the two tables, it can be seen that the majority of components can withstand the maximum internal temperatures. However, the actuators and slave boards have a lower maximum allowable temperature than the derived internal temperature of the LW when operated in lunar regolith simulant. Due to the method used and assumptions made for this analysis, it can be predicted that the internal temperatures are a worst case scenario and are likely higher than the actual values. This prediction is due to several factors. During operation, the individual segments will experience a cool down period due to the nature of peristaltic motion, as all segments will not be firing simultaneously. Also as the LW burrows to new depths in the test bed, the temperature of the test medium immediately

surrounding the segment will be at standard temperature allowing for more heat to transfer out. Furthermore, the actuators and slave boards will be directly attached to the aluminum bulkheads, providing an immediate heat sink. These combined factors allow for the reasonable assumption that all components will be able to withstand the internal temperature of the LW during operation. Please refer to Appendix C for the full Mathcad analysis.

Table 6.4.3.1: LW internal temperature

Medium	Max Internal Temperature (Celsius)
Sand	31.90
Lunar Regolith	110.09

Table 6.4.3.2: Material specific maximum allowable temperature

Unit	Material	Maximum Temperature (Celsius)
Firgelli L16 Actuators	NA	50
Bulkhead	Aluminum 7075-T6	477
Flexible Wall	Fiberglass Epoxy	121
Bolts	Steel	1402
Conduit	Teflon	260
Mounting Brackets	Aluminum 7075-T6	477
Slave Boards	NA	105

6.4.4. Force and Efficiency

Another important factor to this design is the efficiency at which the robot transfers the axial force applied by the actuators into a transverse force through the wall. The efficiency is also important because it determines the power (maximum allowed is 20 Watts) needed by the actuator to achieve the required wall output force of 66 Newtons.

The resistive load due to the central conduit, wiring bus, and the skin were assumed to be negligible. Due to the complexity of analyzing a beam having a parabolic distributed load and compressive axial loads, the sidewall member was treated as combined column buckling and a single normal (equal to the required 66 N) force placed perpendicular to the sidewall member. The method of superposition was used to analyze the loadings separately and then combine them into the required actuator output force. The simplifications aforementioned are shown in Figure 6.4.4.1.

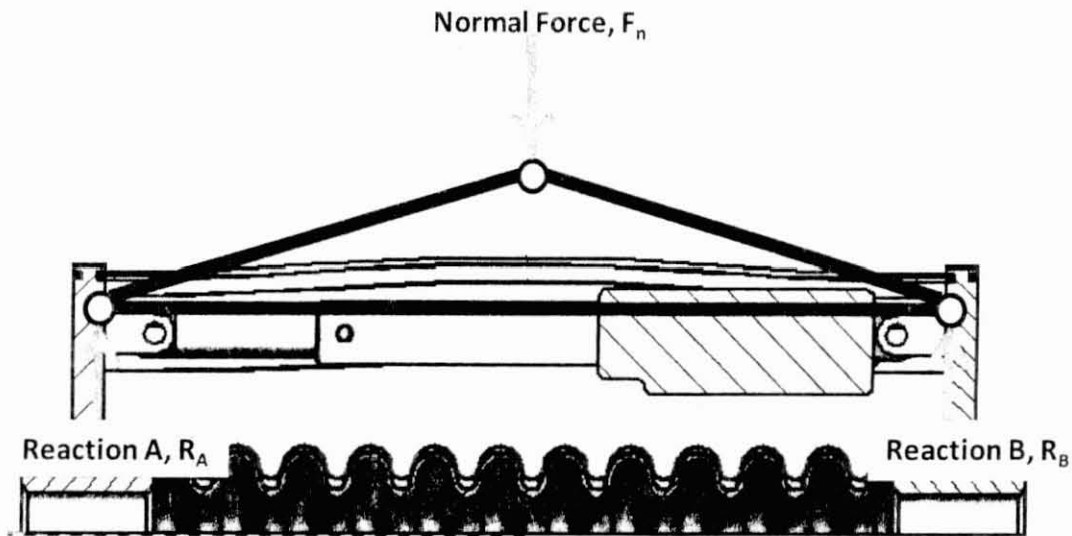


Figure 6.4.4.1: Simplified Force Analysis Model

Because of the initial deflection due to snap fitting the sidewall members into place, the fiberglass walls will have a deflection of approximately sixty-five hundredths of an inch. As the sidewall deflection increases, the moment applied to the fiberglass sidewall grows and the efficiency of the force transfer increases.

From the combination of the column buckling and the three bar linkage analysis, the resulting total linear force from all three actuators is required to be 242 N. Considering the output force is 66 N, that creates a force conversion efficiency of 27.2%. To estimate the power consumption by the three linear actuators running simultaneously, a curve fit of the Fircelli's power curve was produced and evaluated at the output load shown above. The resulting power consumption was 7.15 Watts. Therefore, the force output and maximum power requirements specified by the customer are met. Refer to Appendix D for a complete Mathcad sheet containing all force and power consumption calculations and results.

6.5. Functional Flow Block Diagram

The functional flow block diagram, shown in Figure 6.5.1 and Figure 6.5.2, illustrates the overall general functions performed by the Lunar Wombat during earth based testing. The specific functions performed are as follows:

- 1.0 Equipment Setup – General setup of the LW will include several steps to begin operation.
 - 1.1. Position start tube – A hollow cylinder will be oriented vertically and perpendicular to the test bed.
 - 1.2. Insert LW into start tube – The LW will be placed into the cylinder with the auger facing downward into the test material.
 - 1.3. Attach electronics tether to LW
 - 1.4. Attach electronics tether to surface control unit
- 2.0 Provide power – For earth based testing, electric power from a power supply.
 - 2.1. Clear personnel – To avoid safety concerns, all personnel should be clear of the LW during power-up.
 - 2.2. Provide electric power from surface support unit.

- 3.0 Establish computer control – The LW segments utilize a software package to perform peristaltic motion.
 - 3.1. Start control software
 - 3.2. Validate proper connection from computer to all systems – A preliminary check will be performed to ensure all systems are properly responding to computer outputs.
- 4.0 Initiate auger – Begin rotation of auger into test material
- 5.0 Begin sequence of active segment peristaltic motion – The Lunar Wormbot utilizes a master board and eight slave boards to perform automated peristaltic motion.
 - 5.1. Operator sends signal to master board – Initial signal is sent to the master board to begin motion.
 - 5.2. Master board receives signal – Initial signal is received by master board.
 - 5.3. Master board sends signals to slave boards in sequential order – Initial signal is relayed to each of the slave boards, housed in the active segments, in sequential order.
 - 5.4. Slave boards receive signal – The slave boards receive signal from the master board in sequential order.
 - 5.5. Slave boards send signal to actuators – Each of the eight slave boards sends a signal to the actuators housed in the segment associated with the individual slave board.
 - 5.6. Actuators retract – As the actuators retract, the diameter of the LW increases while the length decreases.
 - 5.7. Actuators expand – As the actuators expand, the diameter of the LW decreases while the length increases.
- 6.0 Burrow – As the segments are immersed into the test material, the segments expand and contract in sequential order to provide peristaltic locomotion.
- 7.0 Collect samples – “Dummy” segments will begin collecting samples at various depths.
- 8.0 Reverse auger and segment motion to return to surface – The LW will reverse its peristaltic motion to return to the surface for sample retrieval and data collection.
- 9.0 Manually dig out – If the LW is unable to be retrieved through segment motion reversal, the device will be dug out of the test material.
- 10.0 Power down – Once surfaced, the LW will be disconnected from the power source.
- 11.0 Remove samples – Samples will be removed from the “dummy” segments once the LW has surfaced and been powered down.
- 12.0 Cleanup – The LW will undergo cleaning and repairs after each mission as needed.
 - 12.1. Inspect and clean outer parts – The exterior of the LW will be inspected for damage and fine particulate matter will be removed from the outer casing.
 - 12.2. Perform repairs as necessary – If damage to the exterior or malfunction of internal parts should occur, maintenance of individual parts will be performed as needed.
 - 12.3. Store in appropriate environment – The LW will be stored in a dry environment at standard temperature and pressure.

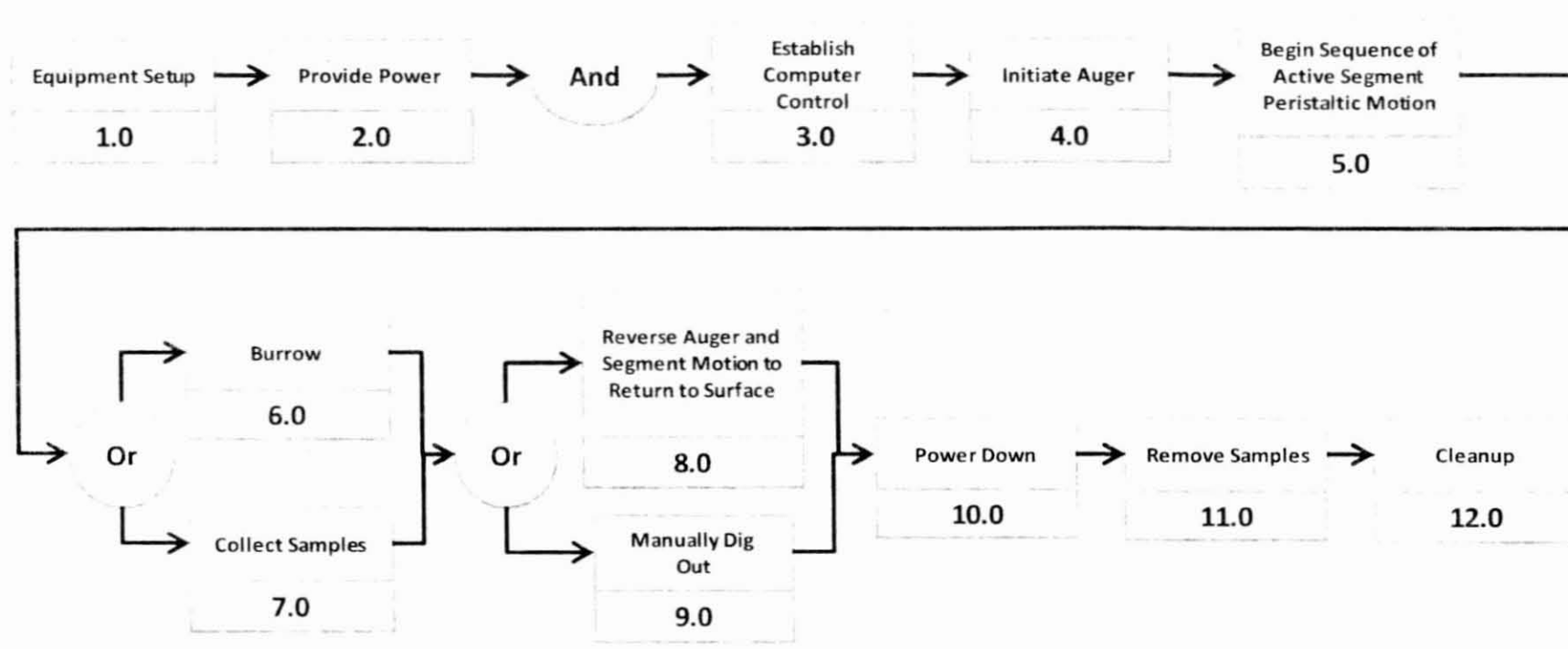


Figure 6.5.1: Functional flow block diagram

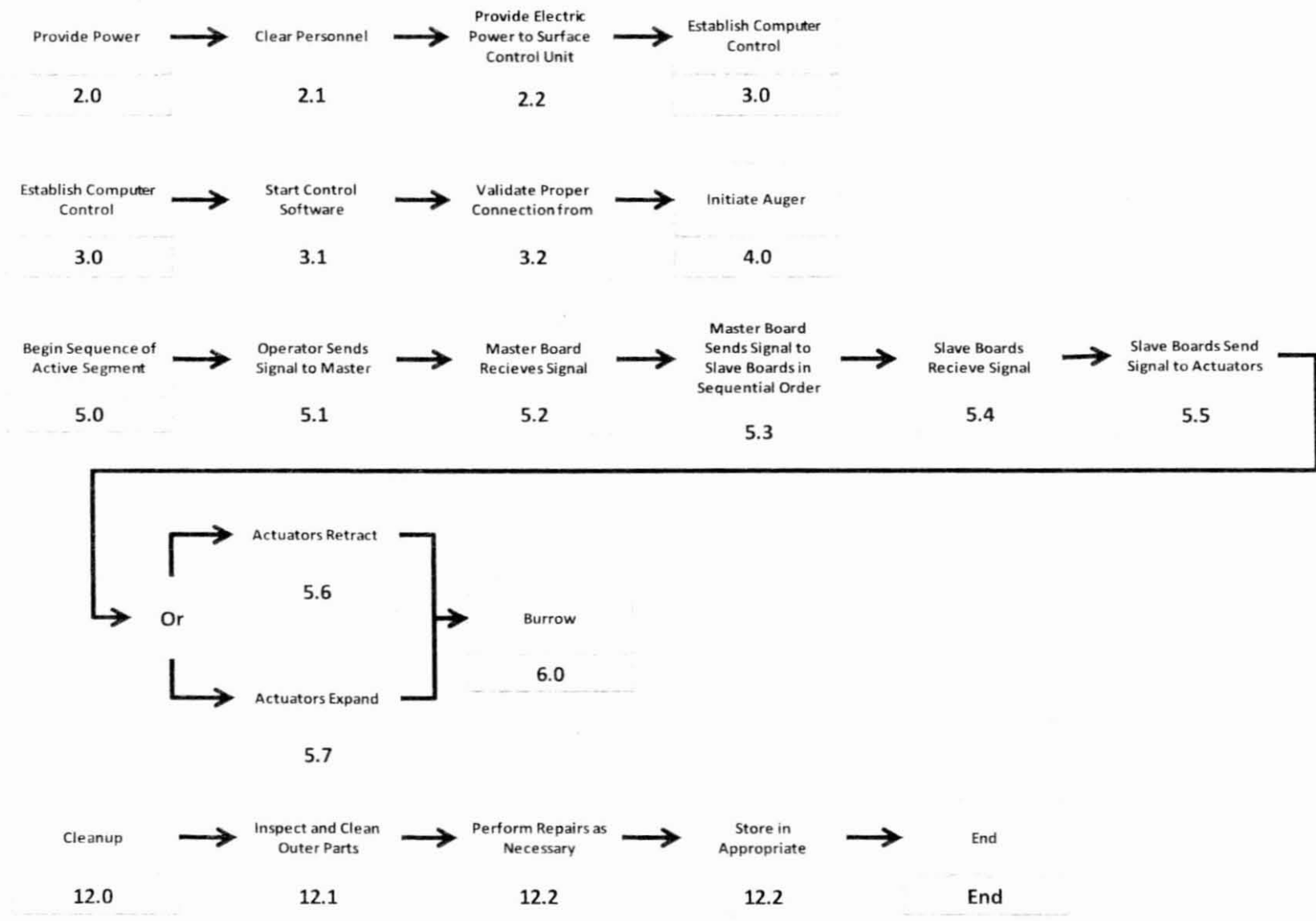


Figure 6.5.2: Functional flow block diagram – second tier

6.6. Interface Requirements

The interfaces of the design contain mainly bolted connections to allow for easy maintenance and assembly. The only other types of connections in the system are snap fit and clamped. The systems connection can be seen in detail below in Figure 6.6.1 and Figure 6.6.2. Some concern has been raised to the snap fit connection of the side wall members, due to the risk of the side wall coming out mid mission. This risk is negligible due to the reduced force required to buckle the side walls since the connection becomes a pinned end situation instead of fixed end. One important characteristic of the interfaces is that between segments, there is a standard three hole pattern found throughout the design allowing the dummy segments to be mounted at any location along the worm.

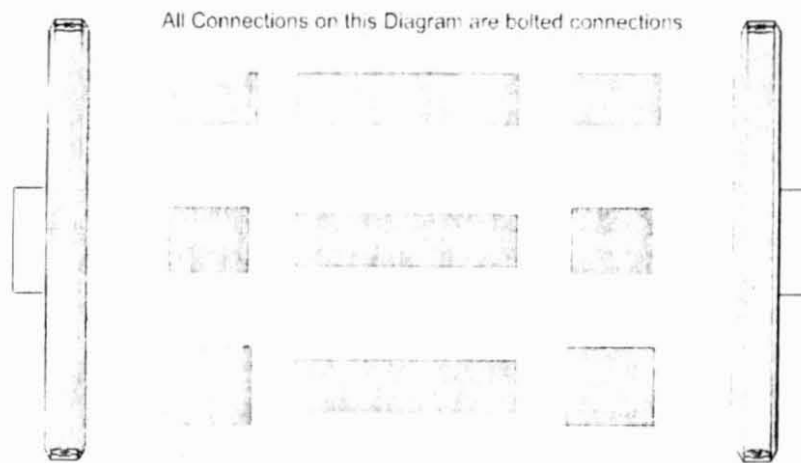


Figure 6.6.1: Actuator to bulkhead connections

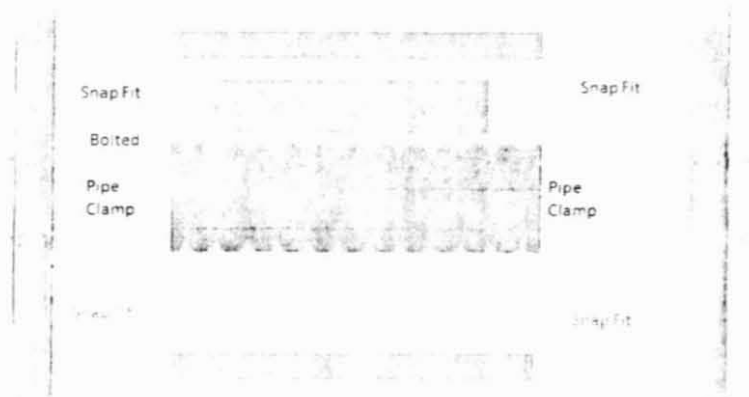


Figure 6.6.2: Systems connections

7. Final Design and Fabrication

The following section provides a detailed description and viewing of the final design of the Lunar Wormbot locomotive segment. Although manufacturing has yet to commence, manufacturing processes and methods as well as safety considerations are addressed. Design verification, reliability, life cycle, and cost are also presented in the following section for the active segment design only.

7.1. Product Design Specifications

The Product Design Specification (PDS) document establishes the purpose, functional requirements, corporate constraints and social, political and legal requirements for the Lunar Wormbot Project. As the project transitions from the preliminary design phase into the final design phase, the PDS will be revised to reflect the final specifications of the Lunar Wormbot. Refer to Appendix E for the initial draft of the PDS, which is to be revised as the project progresses.

7.2. Product Description and Drawings

The Lunar Wormbot is a segmented robot that operates by peristaltic motion. Visually, the entire integrated system looks like a long cylinder with an auger attached at one end (see Figure 7.2.1). Upon closer inspection, the robot can be observed to be comprised of three to eight segments that are jacketed inside of a protective skin. The primary segment type is a locomotive segment.

Locomotive segments (Figure 7.2.2) are modular subsystems that comprise the majority of the robotic system. Peeling the protective skin away reveals a collection of fiberglass strips designed to bend when the aluminum bulkheads on each end compress them. The aluminum bulkheads are the foundational component through which the force is transmitted from the three Firgelli L16 linear actuators and into the fiberglass wall segments. The motion of the actuators is in turn controlled by an electronics slave board that takes its commands from a master controller. The slave board is mounted directly to one of the bulkheads via an aluminum mounting bracket that both grounds the electronics and allows heat dissipation into the body of the LW.

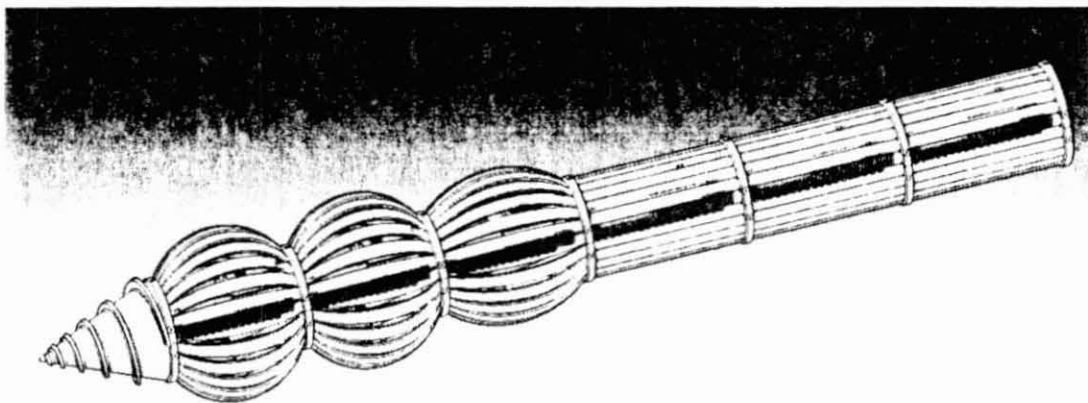
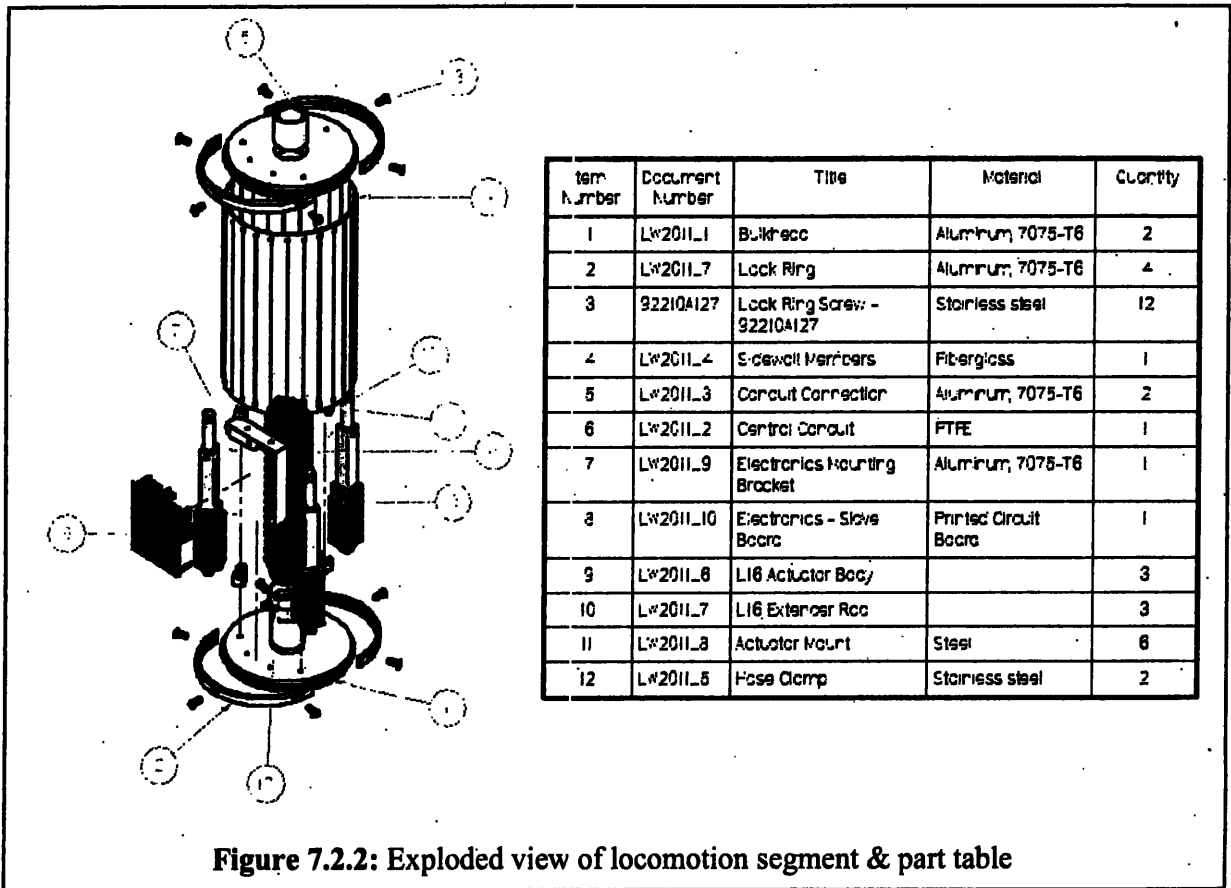


Figure 7.2.1: Lunar Wormbot assembly

Power and communications for the system are supplied through a flexible conduit found in the center of the active segment. The flexibility of the conduit allows it to expand and compress with the segment while maintaining a sealed environment for the wiring and it eliminates any chance of the wire being impinged by the moving parts contained in the segment. All segments of the LW will have the central conduit running through their entire length so that the wiring may be continuous. By having a continuous wire, the chances of a connection failure is reduced. All wiring will terminate into a trailing power and communications tether that will follow behind the LW to transmit power and information down from the surface unit.



7.3. Manufacturing Methods

The production of this project will occur in the West 100 Olin B. King Technology Hall machine shop on the campus of the University of Alabama in Huntsville. A CNC milling machine (Figure 7.3) will be utilized in the production of the bulk heads and clamping rings. A vacuum bag will aid in the manufacturing of the composite materials that make up the side wall members. All other parts will be purchased from various manufacturers. The manufacturing cycle will commence upon the acquisition of parts and is expected to last four weeks. Early verification tests require only one complete segment. Therefore, a single segment will be manufactured, tested, and optimized before the full robot assembly is produced.

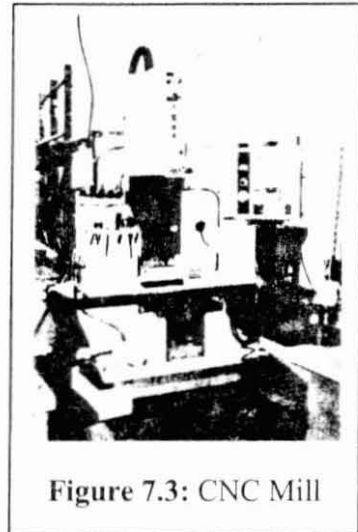
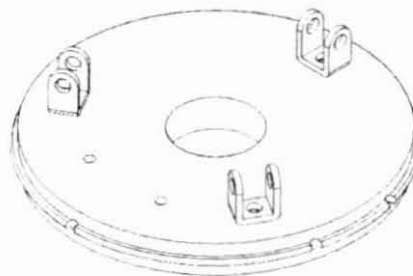


Figure 7.3: CNC Mill

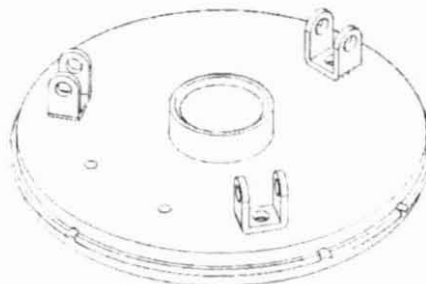
7.4. Assembly and Installation Methods

The assembly will take place in W100 Technology Hall, located on the campus of the University of Alabama in Huntsville. The current design assembly is relatively simple because all connections are bolted together. This means that only basic hand tools are needed for assembly. The assembly can be performed by one person, but to mitigate safety concerns, two people will be required to be present at all times during assembly.

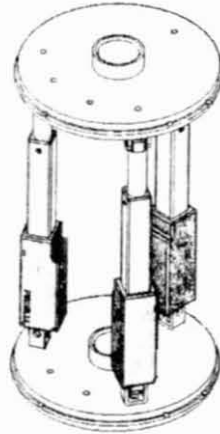
1. The actuator mounting brackets are bolted to the bulkheads in their designed positions and orientations.



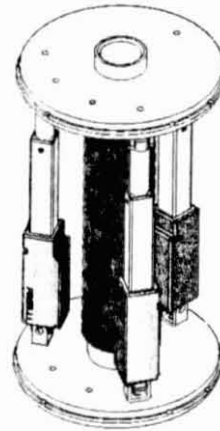
2. The conduit connector is glued into the center holes of the bulkheads.



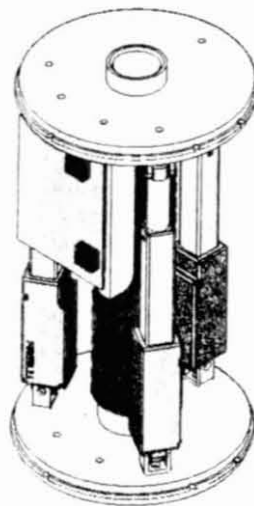
- Both ends of each actuator are bolted into the mounting brackets.



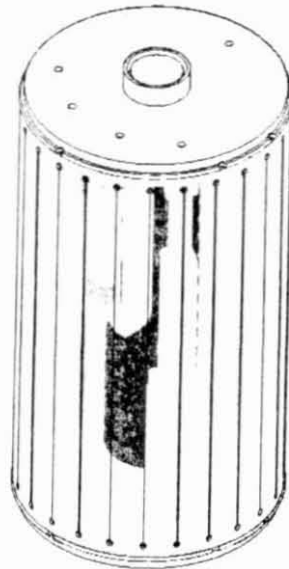
- The conduit is attached to the conduit connectors with pipe clamps.



- The electrical boards are bolted onto the bulkheads in their designed positions and orientations.



6. Each of the twenty five spring wall members are inserted into the trench in each bulkhead



7. Steps 1-6 are repeated for each remaining locomotion segment.
8. The remaining sub-systems, such as the sample collection segments and the head segment are attached at their designed locations.
9. The skin sheath is pulled over the body and held in place by clamp rings.

7.5. Operational and Maintenance Instructions

This product is designed to be a prototype exploratory vehicle. With future software optimization for space based operations the controls should become completely autonomous, eventually reaching the point at which it can be placed on the test medium and allowed to autonomously perform the programmed mission specifications. During the testing phase the robot will operate via a simple control panel feeding commands into an onboard Arduino board.

7.6. Verification Tests

7.6.1. Test 1: Material Validation Test

The purpose of this test was to find the composite side wall's efficiency at transferring longitudinal force to perpendicular force. This test was necessary to determine output force of the L-16's, which in turn determined the needed power of the system. As stated above, the technical analysis suggested an efficiency of 27.2%. After performing the test and analyzing the data, the empirical results yielded a minimum efficiency of 22.4% (Table 7.6.1). These results showed that the system was not as efficient as originally projected, which therefore raises the power requirement of system. This test was run in early February, in room W100 in Technology Hall.

Table 7.6.1: Side wall force and efficiency test

Sample Specifications		
Length (in)	Width (in)	Thickness (in)
7	1	0.041
Start test at 0.5 inch deflection to simulate preload force		
Input Force (lbs)	Output Force (lbs)	Efficiency (%)
2.1	0.47	22.4
2.6	0.67	25.8
3.6	1.1	30.6
4.6	1.5	32.6
5.3	1.8	34.0
5.6	2	35.7
6.2	2.3	37.1
6.7	2.5	37.3
7.4	2.8	37.8
7.8	3	38.5

7.6.2. Test 2: Electronics Functionality Test

This test is a systems check for our electronics to make sure they work before installation. The required equipment will be comprised of a volt meter, oscilloscope, and a power source. All of the equipment is owned by UAH, so an arrangement can be made to get access to it. Once again the cost of this test will stay relatively low. This is not an endurance test, just a systems check, so the expected duration will be around three days.

7.6.3. Test 3: Force Testing

The third test that is planned is scheduled after the completion of the first segment. It is designed to test the force output of a single segment and the strain experienced by the segment. The budget for this experiment is slightly higher than the previous tests at around \$50. This is due to the increase in required equipment. This test calls for load cells, strain gauges, and data recording equipment. Some of this can be borrowed from the school, but since strain gages are permanently affixed, those would need to be purchased. Due to the preparation required to attach strain gages, the duration of this test will be two weeks.

7.6.4. Test 4: System and Controls Test

This test is an overall systems check which will occur once the electronics have been integrated into at least one segment. It will test the extent of three-dimensional motion and the deflection capabilities of the segment. The testing apparatus required will consist of calipers, tape measure, and Faro arm. The expected cost for this test is \$20 – required for the cost of building a jig to hold the segment while it goes through its full range of motion. The duration of this test is expected to be one week.

7.6.5 Test 5: Multi-Segment and Peristaltic Motion Test

This final test is the most important for the scope of this project. It is designed to test the peristaltic locomotion as a system. The current plan is to put a cone on the front of the robot, and bury it vertically in a tube larger than its compressed diameter. The robot will then be activated and peristaltically travel up the tube to the surface. If this test is successful, it will show that the current design can effectively propel itself using peristaltic motion and that it provides enough forward force to preload the ultrasonic drill bit. The equipment for this test consists of a tube larger than the robot and test medium. Due to the size of the tube needed we are budgeting \$163. Considering this is the most important test for the robot, the duration of the test will be approximately three weeks.

7.7. Requirements Verification Matrix

Table 7.7.1: Statement of requirements, verification criteria and methods

Requirement No.	Document	Paragraph	Shall Statement	Verification Success Criteria	Verification Method	Facility or Lab	Performing Organization	Results
R-1	CDD	2.3.1	The LW shall be capable of burrowing through fine particulate matter	1. LW burrows through flour or regolith simulant for 1 meter in any direction without human assistance. 2. LW compacts surrounding soil	1. Measure distance from test start to test finish. 2. Visually inspect for soil compaction.	1. UAH/KSC 2. UAH/KSC	1. UAH 2. UAH	1. TBD 2. TBD
R-2	CDD	2.3.2	The LW shall implement peristaltic locomotion allowing one-dimensional burrowing, and should have segments articulated in three dimensions	1. LW body segment expands and contracts radially with no visual abnormalities. 2. Hoop measurements from expansion to contraction do not exceed 0.5 eccentricity.	1. Visual inspection to insure no abnormalities. 2. FARO® Scanner utilized for shape verification.	1. UAH 2. UAH	1. UAH 2. UAH	1. TBD 2. TBD
R-3	CDD	2.3.3	The LW concept shall be designed for Earth based testing.	1. All material withstand temperatures ranging from 4C to 35C	1. Qualification of materials via parts procurement processing	1. UAH	1. UAH 2. LA Tech	1. TBD 2. TBD
R-4	CDD	2.3.4	The LW shall be capable of taking 50 one gram samples at various depths	1. LW sample segment acquires 10 one gram samples at 0.5m depth without human assistance.	1. LW segment buried at specified depth and activated until criteria met.	1. LA Tech	1. LA Tech	1. TBD
R-5	CDD	2.3.5	The LW shall be capable of utilizing a power source supplying 20 Watts peak power per segment.	1. LW functions in all capacities without using more than 20W power.	1. Connect LW to power source less than or equal to 20W and observe LW function.	1. UAH	1. UAH	1. TBD
R-6	CDD	2.3.6	The LW shall incorporate an ultrasonic drill bit and auger in the head section.	1. LW motion segment interfaced with ultrasonic drill bit and auger.	1. Manufacturing integration procedures includes specified components.	1. LA Tech	1. LA Tech	1. TBD

Continuation of Table 7.7.1

Requirement No.	Document	Paragraph	Shall Statement	Verification Success Criteria	Verification Method	Facility or Lab	Performing Organization	Results
R-7	CDD	2.3.7	The LW shall use an elastic, water-tight skin material capable of insulating internal electrical and mechanical systems from fine particulate matter.	1. No flour or regolith simulants enters the LW body segments during prototype burrow tests.	1. Perform LW functional test in test bed; disassemble LW body segment and determine if any particulate matter has entered.	1. UAH/KSC	1. UAH	1. TBD
R-8	CDD	2.3.8	The LW shall have space to integrate a sensing and navigation package.	1. At least one cubic inch of space in each LW body segment remain for optional specified package.	1. Calibrated measurement equipment to provide dimensions of excess space.	1. UAH	1. UAH	1. TBD
R-12	CDD	2.3.12	The LW shall be analyzed using modeling and simulation techniques prior to prototype testing.	1. Force/stress analysis and modeling to provide parts design allowing specified requirements to be accomplished.	1. Mathcad/Solid Edge/ Solid Works/ Nastran/ Patran modeling and simulation of components	1. UAH	1. UAH	1. Modeling and simulation techniques presented at PDR
R-13	CDD	2.3.13	The LW auger shall be designed to optimize soil displacement and forward motion.	1. LW prototype to burrow at a rate of one foot per hour in any direction.	1. Test start and finish time and distance to be recorded to reflect burrow rate.	1. UAH/KSC	1. LA Tech	1. TBD
R-14	CDD	2.3.14	Individual dummy segments shall be between 50% and 90% of locomotion segment volume.	1. Sample and motion segments fabricated within design specifications and tolerances.	1. Calibrated measurement equipment to provide dimensions of sample and motion segments.	1. LA Tech	1. LA Tech	1. TBD
R-16	CDD	2.3.16	The LW shall produce at least 66 N of force directed perpendicular to the segment's longitudinal axis at the center hinge.	1. LW motion segment provides at least 66 N of force perpendicular to the segment's longitudinal axis at the center hinge.	1. Load cell testing apparatus to verify specified forces in the specified direction.	1. UAH	1. UAH	1. TBD

7.8. Safety

The Lunar Wombat system is designed to primarily function autonomously, therefore the main safety concern is when the LW needs to be serviced or for sample retrieval. Under typical operating conditions there will be very little human interaction with the system thus keeping risk to a minimum. The risk assessment was performed using the Army Standard defined in MIL STD 882B (Figure 7.8.1 and Figure 7.8.2).

7.8.1. Inactive State Safety

Inactive state refers to the LW when it is powered down for storage or transportation. Due to the circular nature of the LW, it can roll thus increasing the probability of falling when in storage or transportation. Therefore, while in storage the LW should be kept at a low height to reduce the risk of damage incurred from falling. In addition, when powered down the linear actuators are not locked into position which creates the possibility of shifting when handled therefore requiring additional care to be taken when handling the LW. The potential shift in the linear actuators also presents the risk of pinching fingers when being handled. Considering the multiple hazards inherit in the LW and its size it is recommended that the LW be lifted by two people.

7.8.2. Active State Safety

Active state refers to when the robot is under power or in the process of being powered on. The simplest risk reduction is to refrain from interacting with the LW except when necessary. When the need arises to interact with the LW, clear situational awareness must be maintained at all times. Clear situational awareness will reduce the risk of pinched fingers from the expanding and contracting gaps between the sidewalls. As with any electrical device there is a small risk of shock, but since the majority of the wiring will be enclosed in a plastic conduit this risk is minimum.

Hazards	Initial Risk Level	Controls	Residual Risk Level
Accidental Drop	5	Designated Hand Holds - Case	10
Simulant Penetration	10	Seal Design	15
Pinch Hazard	9	Warning Stickers	14
Unintentional Power on	14	Lock Out/ Tag out procedure	17
Battery Corrosion	14	Scheduled Maintenance	17
Unintentional Power Loss	19	Redundant Connections/ Handling Standards	20

Figure 7.8.1: Risk analysis matrix

MIL STD 882B		Critical (2)	Marginal (3)	Negligible (4)
Frequent (1)	1	3	7	13
Probable (2)	2	5	9	16
Occasional (3)	4	6	11	18
Remote (4)	8	10	14	19
Improbable (5)	12	15	17	20

Figure 7.8.2: Risk assessment matrix

7.9. Reliability and Life Cycle

The LW prototype must be reliable enough to last many cycles of testing. In the future, the LW will be optimized for lunar soil sampling. Since it will be in a space environment with no manual support, reliability will become a much larger priority. Keeping future design iterations in mind, the system was optimized to eliminate as many points of failure as possible. The design's robustness was also increased by sealing each segment to prevent the test medium from entering all segments should one segment fail. After reviewing the design, the three weakest links in the design were determined to be the skin, the side walls, and the L-16 actuators.

The skin material for this design is currently a leather sleeve. The sleeve will cover the segments to prevent test medium from infiltrating the LW. Therefore, the reliability of the skin to handle abrasion and keep out particles is paramount. Leather was chosen for its durability and resistance to abrasion. For Earth based testing, a leather sleeve will handle all conditions the LW will encounter. For future lunar based operations, a space rated skin material will be designed to handle the harsh lunar conditions.

Another point of concern is the composite side wall material. Due to the lack of fatigue testing equipment available, the reliability of the side wall is assumed to be the same as a similar system used in the UAHuntsville Moon Buggy. The Moon Buggy utilizes a composite leaf spring as a suspension system which undergoes multiple deflections during a race. After one year of operation this suspension system has yet to show signs of fatigue. The loads and the amount of deflection the side walls will experience are much lower than said suspension. Therefore, the side walls should have no problem surviving multiple missions.

The final point of concern is the only moving component, the L-16 actuator. Since all moving parts experience fatigue, the reliability of the actuators is a high priority. Failure of the actuators would lead to a loss of locomotion in a segment. The L-16 actuators are rated by the manufacture for 20,000 cycles at 20% load. The standard load the actuators will be experiencing in this design is 40%. With a burrowing depth of fifteen meters per mission, the actuators will last for eight missions before being replaced. Other causes of loss of locomotion can be seen below in Figure 7.9.1. A detailed failure analysis of the L-16 actuators can be seen in Figure 7.9.2.

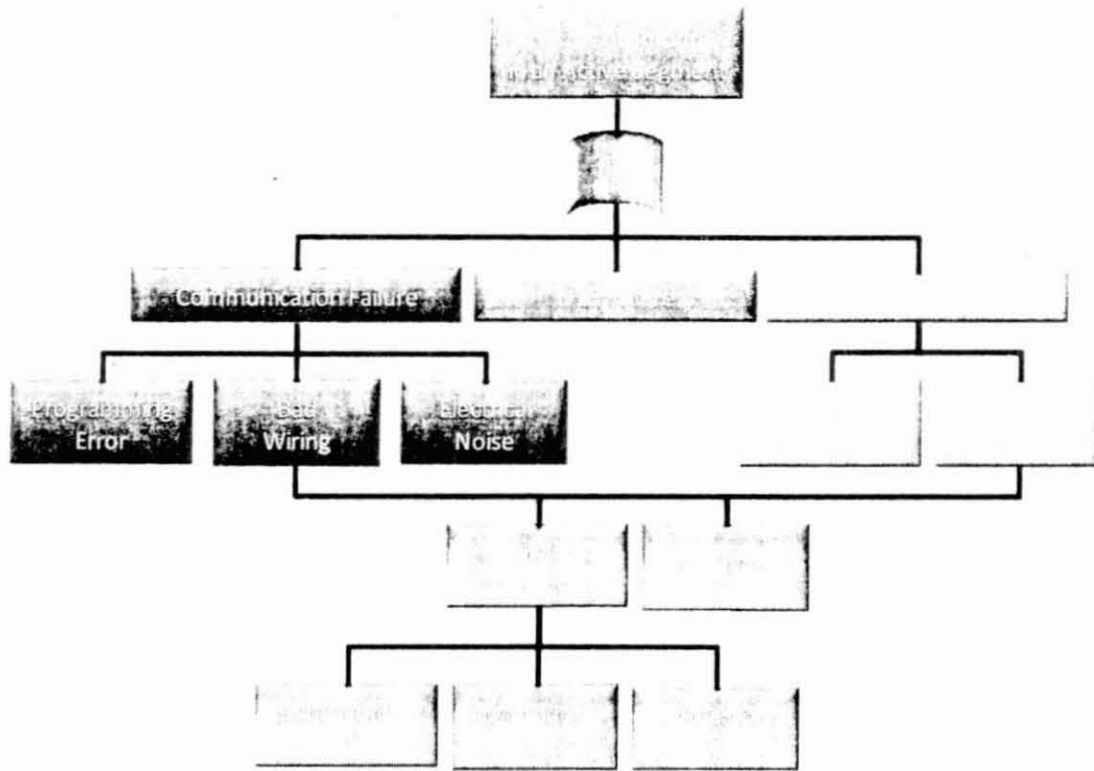


Figure 7.9.1: Lunar Wormbot fault tree analysis

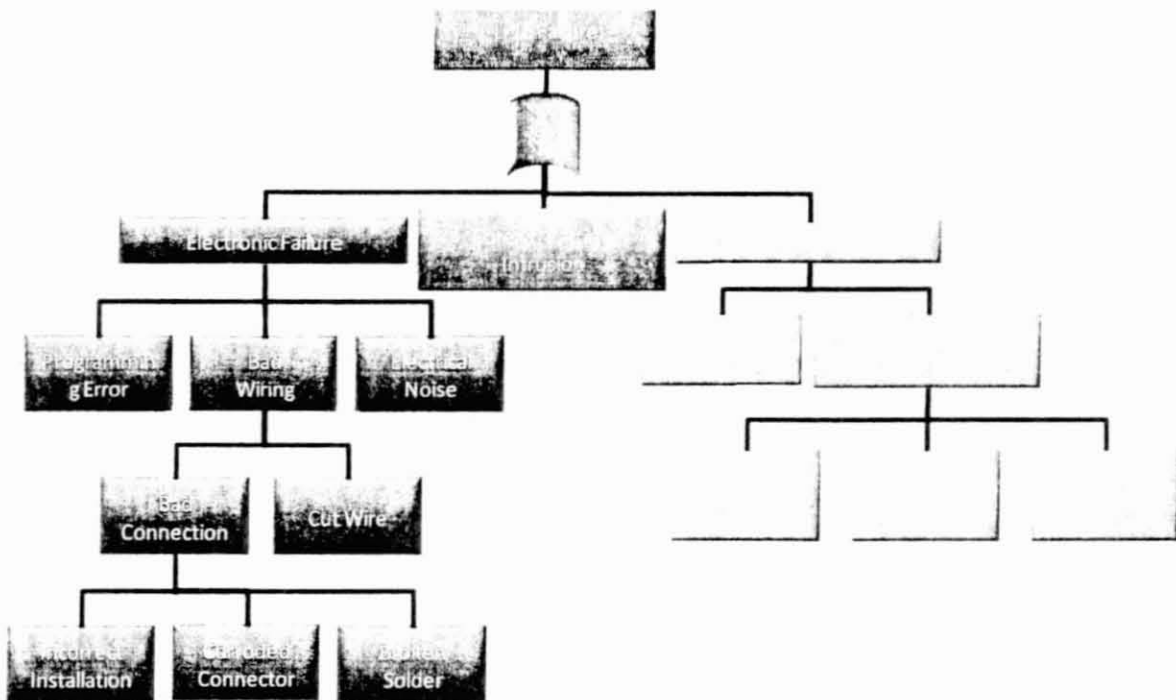


Figure 7.9.2: L-16 Actuator fault tree analysis

7.10. Final Cost/Budget

7.10.1. Parts

The parts required to produce the LW can be summarized into two major categories – electronics and hardware. Electronics consist of the actuators, chips, computer control structures, and associated products (i.e. solder). Items listed as hardware are comprised of solid bodies such as the required bulkheads, screws, and composite materials. These two categories are summarized in Tables 7.10.1.1 below and 7.10.1.2 on the following page.

Table 7.10.1.1: Electronic components

Item	Vendor	Part#	Cost/unit	Qty.	Total	Team Cost
L16-P Linear Actuator	firgelli.com		\$80.00	26	\$2,080.00	\$1,560.00
The MiniBoardPro	expresspcb.com		\$75.00	4	\$300.00	\$300.00
Arduino Mega	sparkfun.com	DEV-09152	\$50.00	2	\$100.00	\$0.00
Propeller Microcontroller	Digikey.com	P8X32A-Q44	\$7.99	8	\$63.92	\$63.92
Full H-Bridge Gate Driver	Digikey.com	Digikey 497-1396-5-ND	\$5.83	16	\$93.28	\$93.28
Analog to Digital Convertor	Digikey.com	Digikey ADC0834CCWM-ND	\$3.33	8	\$26.64	\$26.64
1.23 – 29 V Adjustable Voltage Regulator	Digikey.com	Digikey LP2952AIM-ND	\$4.26	8	\$34.08	\$34.08
Molex Board to Wire Connector	Digikey.com	Digikey WM7648CT-ND	\$0.86	24	\$20.64	\$20.64
X1 - 5MHz Crystal	Digikey.com	Digikey 300-8347-1-ND	\$0.90	8	\$7.20	\$7.20
12V Power Supply	Digikey.com	Digikey 945-1076-ND	\$27.17	1	\$27.17	\$27.17
Solder Paste	Pololu		\$24.00	2	\$48.00	\$48.00
Stencil	Pololu		\$32.00	1	\$32.00	\$32.00
Brushless DC Motor			\$159.60	1	\$159.60	\$159.60
Motor Controller			\$109.00	1	\$109.00	\$109.00
Shipping (estimated at 10% of items)					\$310.15	\$310.15
Total					\$3,411.68	\$2,791.68

Table 7.10.1.2: Hardware

Item	Vendor	Part #	Cost/unit	Qty.	Total	Team Cost
Active Segments:						
7075 AL Plate 0.375"x12"x36"	onlinemetals.com		\$172.39	1	\$172.39	\$172.39
Flange Button Socket Cap Screws - Stainless #10-24x3/8" Pack of 25	McMaster-Carr	97654A141	\$9.25	2	\$18.50	\$18.50
Fiberglass(4oz E Glass)	uscomposites.com	FG-C0450	\$5.15	4	\$20.60	\$20.60
Epoxy resin	uscomposites.com	EPOX-6355563	\$38.50	1	\$38.50	\$38.50
Convolutd (Spiral) Flexible White Tubing Made with Teflon® PTFE	McMaster-Carr	51155K271	\$30.17	8	\$241.36	\$241.36
Low Pressure Spring Hose Clamps 1.125" (pack of 25)	McMaster-Carr	5324K23	\$5.09	1	\$5.09	\$5.09
Latex Coating - 32 oz.	liquidlatex.com	912	\$23.39	1	\$23.39	\$23.39
Other:						
Shipping (estimated @ 10% of items)					\$51.98	\$51.98
					Total	\$571.81
						\$571.81

7.10.2. Manufacturing

Primary costs associated with manufacturing occur in the payment of machinist hours involved in production of the segment bulkheads, laying up of composite side walls, and assembly. Since most, if not all, construction can be accomplished utilizing the skills of this design team, the expected costs are associated only with expendable tooling. Expected manufacturing expenses are listed in Table 7.10.2.

Table 7.10.2: Manufacturing costs

Item	Vendor	Part #	Cost/unit	Qty.	Total	Team Cost
Machinist's Time (\$/hr)	NSSTC	Bulkhead x10	\$60.00	15	\$900.00	\$0.00
Layup of Fiberglass (\$/hr)			\$30.00	10	\$300.00	\$0.00
Assembly (\$/hr)			\$30.00	10	\$300.00	\$0.00
1/2" End Mill - Aluminum Cutting	MSC Direct	MSC #: 97651749	\$40.64	2	\$81.28	\$81.28
Hand Tap - Tapered #10-24	MSC Direct	MSC #: 74328261	\$6.16	3	\$18.48	\$18.48
Shipping & Handling	MSC Direct		\$20.00	1	\$20.00	\$20.00
					Total	\$1,619.76
						\$119.76

7.10.3. Testing

Five tests are expected to be performed to verify the design and operability of the LW before delivery. Each test as explained in section 7.6 is designed to verify that the LW meets the pertinent design requirements listed in the CDD in Appendix A. Additionally, travel was budgeted for testing as it is hoped to utilize the regolith test bed at the Kennedy Space Center in Cape Canaveral, Florida. Expected testing and travel costs are located in Table 7.10.3.

Table 7.10.3: Testing

Test (Associated Materials)	Vendor	Part #	Cost/unit	Qty.	Total	Team Cost
Test 1: Material Validation Test (Support jig)			\$15.00	1	\$15.00	\$15.00
Test 2: Electronics Functionality Test (Wire, computer setup)			\$10.00	1	\$10.00	\$10.00
Test 3: Force Testing (strain gages, force sensors, holding jigs, etc.)			\$50.00	1	\$50.00	\$50.00
Test 4: System and Controls Test (Holding Jigs, Faro Arm, Measuring equipment)			\$50.00	1	\$50.00	\$50.00
Test 5: Multi-Segment/Peristaltic Motion Verification (Wiring bus, Jigs, Sandbox)			\$100.00	1	\$100.00	\$100.00
6" OD x 5 3/4" ID Acrylic Tubing (\$/ft)	usplastic.com	44550	\$10.48	6	\$62.88	\$62.88
Travel to Kennedy Space Center (KSC)						
Roundtrip Flight - Huntsville,AL to Orlando,FL			\$250.00	3	\$750.00	\$750.00
Hotel (\$/night) *estimated			\$100.00	8	\$800.00	\$800.00
Total					\$1,837.88	\$1,837.88

7.10.4. Engineering Effort

Cost associated with engineering design can be shown in the following two tables. This cost was determined by utilizing the activity plans of section 3 generated Microsoft Project. Each activity was complemented by a resource, or team member, and an accompanying cost per hour. It was assumed that each resource worked forty hours per week when utilized. Table 7.10.4.1 corresponds to Figure 3.1 in which the total cost is shown below. Table 7.10.4.2 corresponds to Figure 3.2 in which the total engineering cost can be seen on the following page.

Table 7.10.4.1: Engineering costs associated with concept to preliminary design phases

	August	September	October	November	December	Total
Lunar W/robot						
Documentation						
CDD Draft	\$720.00	\$1,020.00	\$810.00	\$480.00		\$3,030.00
CRR Presentation	\$720.00	\$570.00				\$1,290.00
CDD Final		\$330.00				\$330.00
CDR Presentation		\$750.00	\$780.00			\$1,530.00
Product Design Specifications		\$900.00	\$1,620.00	\$660.00	\$510.00	\$3,690.00
Preliminary Design Analysis Report			\$180.00	\$270.00		\$450.00
PDR Presentation			\$180.00	\$270.00		\$450.00
Final Design Reports			\$180.00	\$270.00		\$450.00
Manufacturing Processes				\$1,850.00	\$1,650.00	\$3,510.00
Fabrication Reports					\$300.00	\$300.00
Design Analysis						
Thermal Analysis		\$675.00	\$4,515.00	\$2,160.00		\$7,350.00
Stress Analysis		\$1,020.00	\$2,595.00	\$1,290.00		\$4,905.00
Force Analysis		\$675.00	\$4,515.00	\$2,160.00		\$7,350.00
Life-cycle		\$1,080.00	\$2,580.00	\$540.00		\$4,200.00
X-TOOLSS						
Conceptual Design and Parameters		\$1,560.00	\$180.00			\$1,740.00
Critical Parameters			\$1,260.00			\$1,260.00
Optimization Routine and Code			\$1,200.00	\$2,220.00	\$2,160.00	\$5,580.00
Run X-TOOLSS and Refine Routine				\$2,220.00	\$640.00	\$2,860.00
CAD						
Conceptual Design		\$1,920.00	\$360.00			\$2,280.00
Preliminary Design			\$1,260.00	\$450.00		\$1,710.00
Final CAD Design				\$1,110.00	\$1,350.00	\$2,460.00
Manufacturing Processes						
Price Estimates			\$225.00	\$1,050.00	\$1,350.00	\$2,625.00
Order Parts		\$180.00	\$330.00	\$1,050.00	\$1,350.00	\$2,910.00
Manufacture						
General Research						
Patent Research	\$2,880.00	\$4,710.00	\$150.00			\$7,740.00
Existing Product:	\$2,880.00	\$4,710.00	\$1,350.00			\$8,940.00
Activity Plan						
Tasks	\$720.00	\$960.00	\$660.00	\$450.00		\$2,790.00
Scheduling	\$720.00	\$960.00	\$660.00	\$450.00		\$2,790.00
Total	\$8,640.00	\$22,020.00	\$25,590.00	\$18,960.00	\$9,510.00	\$84,720.00

Table 7.10.4.2: Engineering costs associated with final design and fabrication phases

	January	February	March	April	May	June	Total
Interim Design Review							
Critical Design Phase							
CDD Revision	\$1,087.50	\$810.00					\$1,897.50
Thermal Analysis	\$1,800.00	\$1,440.00					\$3,240.00
Material Validation Test	\$840.00	\$1,140.00					\$1,980.00
Force Analysis	\$1,777.50	\$1,110.00					\$2,887.50
CAD Completion	\$465.00	\$780.00					\$1,245.00
Design Completion							
Critical Design Review							
Fabrication Phase							
Parts Procurement		\$1,440.00					\$1,440.00
Fabrication Processes Completion		\$480.00					\$480.00
Safety Review		\$240.00					\$240.00
Segment Fabrication		\$11,520.00	\$8,840.00				\$20,160.00
Testing Phase							
Electronics Functionality Test		\$960.00					\$960.00
Force Test		\$960.00					\$960.00
System and Controls Test			\$1,800.00				\$1,800.00
Multi-seg / Peristaltic Motion Test			\$1,440.00				\$1,440.00
Surface Navigation Test			\$1,080.00				\$1,080.00
Ship Test Segment to LA Tech							
NASA ESMD Competition Report							
Product Readiness Review							
Systems Integration (UAH)							
All Systems Test (UAH)				\$7,200.00			\$7,200.00
X-TODLSS Analysis			\$5,760.00	\$360.00			\$6,120.00
PDS Revision				\$2,880.00			\$2,880.00
Patent Disclosure Form				\$2,880.00			\$2,880.00
Lunabotics Testbed					\$7,200.00		\$7,200.00
Total	\$5,970.00	\$20,880.00	\$18,720.00	\$13,320.00	\$7,200.00		\$66,090.00

Table 7.10.5: LW cost summary

Item	Total	Team Cost
Table 7.10.1.1: Electronics	\$3,411.68	\$2,791.68
Table 7.10.1.2: Segment Parts and Hardware	\$571.81	\$571.81
Table 7.10.2: Manufacturing Cost	\$1,619.76	\$119.76
Table 7.10.3: Testing Cost	\$1,837.88	\$1,837.88
Table 7.10.4.1: Preliminary Phase Engineering Effort	\$84,720.00	\$0.00
Table 7.10.4.2: Final Design and Fabrication Phase Engineering Effort	\$66,090.00	\$0.00
Total	\$158,251.14	\$5,321.14

7.10.5. Summary of Project Costs

A summary of the cost associated with the materials, manufacturing, and testing of the LW is shown in table 7.10.5. The team cost shown is considerably lower than the total cost. The total cost references what the LW would cost if produced by a corporation. The LW team was able to negotiate a discount of twenty dollars per actuator. The team also was supplied the Arduino Mega control board by the customer representative, Blaze Sanders. Manufacturing costs are significantly reduced due to it being done in house by team members. Since the team is comprised of unpaid students, the preliminary and final design phase costs nothing.

7.11. STEM Outreach

One form of outreach conducted was through the high school level robotics competition FIRST. The team used this venue to help teach high school students basic engineering principles, critical thinking, and problem solving skills. The UAH team mentored Team 3319 Grissom High Robotics during the 2010 build season. This venue covers all aspects of engineering from basic mechanics, electronics, and pneumatics to full systems engineering.

8. Problems and Solutions

8.1. Parts Procurement

Problem: Availability of funding.

Solution: Keep dialogue open with funding agencies.

Problem: Purchase order process requires large amounts of time.

Solutions: Incorporate extra time into schedule and check in with purchasing often. Limit project to a scope capable of being accomplished with parts acquired from local vendors.

8.2. Technical Analysis

Problem: Complicated 3-D systems with composites

Solution: Allow assumptions to get into ballpark and then refine through experimental analysis.

Problem: No defined prioritization of analysis. Many analysis decisions were based on who the information was being presented to rather than overall relevance to the design.

Solution: Develop priority hierarchy based entirely on relevance to design.

8.3. Manufacturing

Problem: Complex logarithmic spiral on auger requires use of either a metal rapid prototype or a 4-5 axis milling machine.

Solution: Minimize design complexity (perhaps not a logarithmic curve).

Problem: Cannot be done without materials.

Solution: See Parts Procurement Problems and solutions

Problem: Composites can be highly variable unless constructed in high tolerance facilities.

Solution: Determine acceptable tolerance range and consider alternate materials.

8.4. Assembly

Problem: Integration of parts produced by other teams.

Solution: Clear communication.

8.5. Verification Test

8.5.1. Material Validation Test

Problem: Broken equipment (i.e. column buckling machine).

Solution: Alternative methods with higher degrees of uncertainty were utilized.

8.6. Lessons Learned

Efficiency of the team was greatest when large tasks were broken down into small segments which were clearly delegated. Early familiarization of the NASA Systems Engineering Engine allowed the team to comprehend the structure and roles of the project. Establishing a relationship with a customer representative produced timely answers to design queries.

9. Conclusion

9.1. Summary

The Lunar Wombat locomotive segment will utilize linear actuators to allow movement by peristaltic motion. Top level requirements for the mission include peristaltic motion as a mode of transportation, force output by the sidewalls, and ability to burrow without internal particle contamination. Most of the safety concerns associated with the project revolve around the manufacturing stage.

9.2. Design Uncertainties

Corrosion: The area most likely to be affected by corrosion is the interface between the actuator mounts and the aluminum bulkhead. This location is noted as a space subject to both crevice and galvanic corrosion. Crevice corrosion is minimized by the use of a recommended storage environment. Galvanic corrosion is to be reduced by the implementation of stainless steel bolts.

Fatigue: The sidewall members will be most susceptible to fatigue due to cyclic loading. Further consideration will be required, however at this time it is recommended that the life of all structural members, sidewall and bulkheads, be limited to the life of the actuators, or 20,000 cycles.

Actuator Failure: Some uncertainty exists due to tensile loading in the actuators. Testing will verify that the correct actuator type was specified for the application.

Sampling Segments and Auger: These items may require final optimization for full functionality with the locomotive segments.

9.3. Recommendations

The skin of the Lunar Wormbot should be noted as a continuous variable, because it allows the LW to be tailored to its operating environment (i.e. Europa, Titan, etc.). This design is noted as a test bed in which optimization and testing of this unit will yield data useful in future developmental prototypes.

10. Acknowledgements

Kirk Biszick – Material Testing Advisor

Adam Burt – X-TOOLSS Support

Dr. Christina Carmen – UAHuntsville MAE 491/492 Instructor and Team Advisor

Steve Collins – Manufacturing Guidance

Ben DiMiero – X-TOOLSS Support and NASA Contact

Dr. Jessica Gaskin – NSSTC Project Head

Michael Kuhlman – Summer LW Proposal Team

Blaze Sanders – Customer/NSSTC Representative

Dr. Michael Tinker – NASA MSFC Thermal and Mechanical Analysis Branch Chief

Dr. Francis Wessling – Thermal Analysis

Lafe Zabowski - Summer LW Proposal Team

11. References

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1
2
3 **Appendix A: Concept Description Document (CDD)**

4 **Concept Description Document**

5 **Lunar Wormbot Project**

6 Prepared by

7 MAE 491/492 Team 1

8 The University of Alabama in Huntsville

9 Huntsville, AL

10 Customer Representative:

11 Blaze Sanders

12 NASA

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14 Email: blaze.sanders@solarsystemexpress.com

15
16
17
18 This Concept Description Document is developed for use in a class at the University of
19 Alabama in Huntsville and does not constitute a legal agreement or imply direction to
20 perform work by a Government Agency.

21

Revision A

22 **Concept Description Document Approval**

23 The undersigned agree that the attached Concept Description Document as marked will be the
24 basis for the MAE 491/492 Class Project. From this time forward, any questions or clarifications
25 concerning the Concept Description Document shall be submitted in writing through the MAE
26 491/492 Instructor to the Customer Representative and the answer distributed to all MAE
27 491/492 participants in writing.
28

29 To change the Concept Description Document after signatures are completed shall require that
30 the change be stated in writing and that a person authorized by every one of the signers below
31 endorse the change with their signature. The revision will be labeled uniquely and distributed to
32 all participants simultaneously.
33

34 The original document will be kept on file with the UAH Instructor. All signers will receive a
35 copy of the original document.
36
37

38 _____ /
39 Blaze Sanders, Customer Representative/ Technical Advisor, NASA
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65 Dr. Christina Carmen, MAE 491/492 Instructor
66
67

Revision A

68 1. **SCOPE** This specification establishes the requirements for the UAH team's design
69 completion for the Lunar Wormbot Project. The mission of the Lunar Wormbot (LW)
70 Project is to design a prototype of a robotic burrowing worm in order to prove the
71 concept on Earth using a lunar regolith simulant. The LW consists of a piezoelectric
72 ultrasonic drill, a conical auger, and multiple elongating segments mimicking the
73 peristaltic motion of an earthworm. One key function of the LW is to retrieve lunar
74 samples taken from various depths within the lunar surface, for either in-situ analysis or
75 for return to Earth. The drill bit will both loosen the regolith and fracture large rocks
76 encountered. An auger will displace the regolith, facilitating the robot's ability to tunnel.
77 The multiple segments of the LW will allow movement in a specified direction by
78 providing a preload force for the drill and auger as well as assisting in the displacement
79 of regolith. The UAH team will be responsible for designing the active segment sub-
80 system of the LW Project but will provide descriptions and limited requirements of the
81 overall system.

82 2. **REQUIREMENTS**

83 2.1 **System description:** The Lunar Wormbot is described in terms of its physical and
84 functional relationship to other systems required to perform the intended mission.

85 2.1.1 **Physical description:** This is a mechanical-robotic implement which has a very low
86 aspect ratio, resembling a mechanical earthworm. The LW consists of an auger on
87 its head section, and several identical active segments thereafter capable of
88 changing their diameter and length. The LW will consist of an aluminum skeleton
89 surrounded by a composite skin. The current LW concept will be approximately 4 to
90 6in. in diameter, 50 to 100in. long, and will have a mass of approximately 10 to
91 30kg^[1]. All dimensions are approximate and would optimally be smaller and lighter.

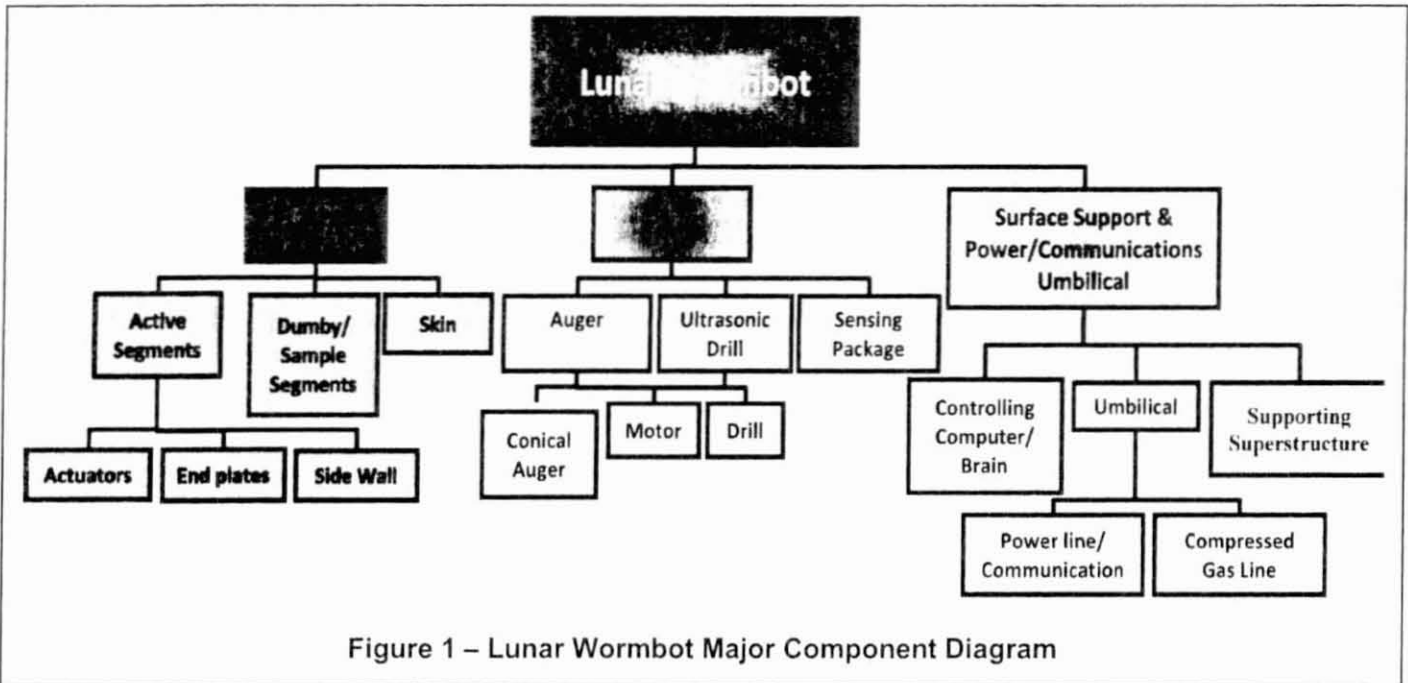
92 2.1.2 **Functional description:** The LW is a concept for subterranean exploration on the
93 lunar surface. The auger-bit assembly at the head of the LW is used to break up
94 regolith and small rocks, and transport that material behind the head. Thereafter, the
95 segments of the LW expand and contract in a sequential, peristaltic fashion in order
96 to generate forward motion. A mounted sampling segment allows soil samples to be
97 collected and transported for analysis.

98 2.1.3 **Mission Statement:** The project goal is to lead to knowledge enabling a burrowing
99 robot to operate on the lunar surface to gather soil samples. Leading to that goal,
100 and staying within the scope of the time period of this project, a single, prototype LW
101 will be produced for earth based testing. This robot will be considered successful in
102 its mission if it offers the ability to burrow through a fine particulate soil simulant,
103 return testing data leading to improvements in design, and exhibits the robustness
104 necessary for space based soil sampling. The goal of the UAH team is to design
105 and fabricate a functional active sub-system prototype.

106 2.2 **Major component list:** The Lunar Wormbot will consist of three major assemblies, of
107 which two will be considered by the UAH and Louisiana Tech teams for design and
108 implementation. These three are the Body, Head, and Surface Support structure. Due to
109 the relative separateness of the Surface Support structure, it will be viewed as its own
110 major system to be developed once the viability of the wormbot system has been
111 proven. Hence, only the Body and Head will be considered in detail with the Surface

Revision A

112 Support structure generally described to outline important features. Figure 1 shown
 113 below is a diagram of the major component list of the proposed LW prototype.



114 2.2.1 **Head:** The head shall be the foremost portion of the wormbot. It will be the primary
 115 drilling and regolith moving portion.

116 2.2.1.1 **Auger:** The auger shall have a conical shape to displace the regolith to the sides
 117 of the wormbot. Also, it will have an optimized logarithmic screw thread to further
 118 displace regolith and encourage forward motion.

119 2.2.1.2 **Ultrasonic Drill:** A drill capable of breaking up larger, harder objects in the regolith
 120 will be located on the foremost point of the head.

121 2.2.1.3 **Motor:** A rotary motor shall drive both the Auger and drill.

122 2.2.1.4 **Sensing Package:** Additional space should be incorporated into the head to allow
 123 for future addition of a computing brain and sensing package.

124 2.2.2 **Body:** The body shall comprise the majority of the wormbot's volume and length and
 125 will be segmented in design. It shall be comprised of Active Segments and Dummy
 126 Segments. A composite Skin shall comprise the third major component of the Body.

127 2.2.2.1 **Active Segments:** Active Segments will provide the forward motive force via
 128 sequenced contraction and expansion resulting in peristaltic motion. At minimum,
 129 the Active Segments will be comprised of:

Revision A

130 **Actuators:** The Actuators will expand and contract the segment to produce a
131 forward force and a normal force on the walls of the burrow.

132 **Bulkheads:** A pair of bulkheads will divide one segment from another and
133 provide the coupling system to join one segment to the next.

134 **Side Wall:** The outer wall of the segment will be the member through which the
135 force is directed outward and into the soil of which it is to burrow. Thus it must be
136 constructed of either a springy, durable material or of hinged plates.

137 2.2.2.2 **Dummy/Sampling Segments:** Dummy segments will not play an active role in the
138 movement of the wormbot. Their mission purpose is to gather regolith samples
139 during the wormbot's descent and retain them for collection upon return to the
140 surface.

141 2.2.2.3 **Skin:** Due to the very fine and abrasive nature of regolith, the skin will need to be
142 very tough and abrasion resistant, flexible, and as nearly impervious to fine dust as
143 possible.

144 2.2.3 **Surface Support Structure:** A support structure will be located on the lunar surface.
145 This structure will house the main computing and communications brain of the
146 wormbot, supply power, and potentially provide some consumables such as
147 compressed gas via a tethered umbilical.

148 2.3 Performance Characteristics.

149 **The team responsible for fulfilling the following listed requirements is specified at the**
150 **end of each requirement.**

151 2.3.1. Requirement 1. The LW shall be capable of burrowing through fine particulate
152 matter. (UAH)

153 2.3.2. Requirement 2. The LW shall implement peristaltic locomotion allowing one-
154 dimensional burrowing, and should have segments articulated in three dimensions.
155 (UAH)

156 2.3.3. Requirement 3. The LW concept shall be designed for Earth based testing. (UAH,
157 LA Tech)

158 2.3.4. Requirement 4: The LW shall be capable of taking 50 one gram samples at various
159 depths. (LA Tech)

160 2.3.5. Requirement 5: The LW shall be capable of utilizing a power source supplying 4
161 Watts peak power per segment. (UAH)

162 2.3.6. Requirement 6: The LW shall incorporate an ultrasonic drill bit and auger in the head
163 section. (LA Tech)

Revision A

- 164 2.3.7. Requirement 7: The LW shall use an elastic, water-tight skin material capable of
165 insulating internal electrical and mechanical systems from fine particulate matter.
166 (UAH)
- 167 2.3.8. Requirement 8: The LW shall have space to integrate a sensing and navigation
168 package. (UAH, LA Tech)
- 169 2.3.9 Requirement 9: The LW should be capable of returning to the surface with all
170 acquired samples. (UAH)
- 171 2.3.10 Requirement 10: The LW should apply mechanical force by means of motors or
172 actuators situated perpendicular to its longitudinal axis. (UAH)
- 173 2.3.11 Requirement 11: The LW design should be optimized using X-TOOLSS software.
174 (UAH)
- 175 2.3.12 Requirement 12: The LW shall be analyzed using modeling and simulation
176 techniques prior to prototype testing. (UAH)
- 177 2.3.13 Requirement 13: The LW auger shall be designed to optimize soil displacement and
178 forward motion. (LA Tech)
- 179 2.3.14 Requirement 14: Individual dummy segments shall be between 50% and 90% of
180 locomotion segment volume. (LA Tech)
- 181 2.3.15 Requirement 15: The LW should avoid using consumable mass (i.e. compressed
182 inert gas vented from the machine). (UAH, LA Tech)
- 183 2.3.16 Requirement 16: The LW shall produce at least 66 N of force directed perpendicular
184 to the segment's longitudinal axis at the center hinge. (UAH)
- 185 2.3.17 Requirement 17: The LW should be designed to withstand temperature extremes on
186 the lunar surface. (UAH, LA Tech)
- 187 **2.4 Operational Characteristics.**
- 188 **2.4.1 Facilities, transportation, and storage**
- 189 2.4.1.1 **Facilities**: The LW construction can be done in a standard machine shop. The
190 auger will need either Rapid prototyping or 5-axis machining to get the desired
191 logarithmic spiral. Support facilities for this project should be minimal. A testing
192 area and a laptop will suffice for testing purposes.
- 193 2.4.1.2 **Transportation**: The LW shall be small enough to fit into the back of most cars.
194 Under current concepts it will be at least a 2 person lift. It is recommended that a
195 standard cart is used for room-to-room transportation.
- 196 2.4.1.3 **Storage**: The LW shall be stored in standard room conditions while not being
197 tested.
- 198 2.4.2 **Installation/Removal**: An apparatus to position, initiate, and extract the LW shall be
199 designed after viability testing is performed. For testing circumstances, the LW may
200 initially be started partially buried into the testing medium or via a guide tube.

Revision A

- 201 2.4.3 **Reliability:** The LW shall be reliable enough to survive one voyage down to a depth
202 of 15m and the return trip. Additional voyages would be a bonus with an ideal life
203 expectancy of up to two years.
- 204 2.4.4 **Mission Reliability:** N/A
- 205 2.4.5 **Storage Reliability:** The LW shall be capable of being stored for long periods, in
206 excess of 3 years, without failure.
- 207 2.4.6 **Safety:** The LW is a self-propelled burrowing apparatus with many sharp edges and
208 pinch points; therefore, the LW shall not be in operation during transportation. Also,
209 the wiring harness will necessarily flex with the peristaltic motion of the robot.
210 Therefore, before the robot is serviced or the casing is opened, the power supply shall
211 be disconnected and the electronics grounded to eliminate the chance for electric
212 shock.
- 213 2.4.7 **Mechanical Safety/Hazardous Materials:** The largest mechanical hazards are
214 pinch points and sharp edges. Therefore, no one should be near the LW during
215 operation.
- 216 2.4.8 **Drop Safety:** Due to the significant mass of the LW, it is recommended that all
217 individuals working on or around it should be wearing safety shoes. Also, structural
218 damage and skin integrity could be compromised if the LW is dropped from any
219 significant height.
- 220 2.4.9 **Human Performance/Human Engineering:** The Human interaction with the LW
221 should be minimal. Interaction should be limited to sample acquisition, skin
222 repair/replacement, and system maintenance. During testing, human interaction will
223 be high but should not be a driving force in the design due to its future goal of
224 autonomous operation.
- 225 2.4.10 **Personnel:** The personnel envisioned for this project will be relatively minimal. Three
226 distinct phases can be identified with differing personnel requirements and are as
227 follows:
- 228 2.4.10.1 **Design and Manufacture:** This phase of the LW should require the
229 involvement of approximately ten individuals. Five of those are the members of
230 this team who will frequently come into contact with the design and assembly
231 processes. For the production of the components of the LW, it is estimated that
232 between one and two machinists will be actively employed on an as needed
233 basis. Finally, approximately four technical advisors may be included at any
234 one time during this phase, and though they may come in contact with the LW
235 periodically, they will primarily offer remote assistance.
- 236 2.4.10.2 **Testing:** During this phase of operation only a handful of individuals will be
237 required. The jobs will primarily be to monitor and process data from the LW as
238 it burrows through various soil simulant. A qualified service technician will also
239 be required to effect necessary repairs and upgrades.
- 240 2.4.10.3 **Missions:** By this point the LW should operate nearly autonomously and will
241 only require human interaction when its sensors detect a problem and needs
242 servicing or when it has returned and sample collections must be made.

Revision A

243 2.4.11 **Training**: Minimal training should be required to operate the apparatus because of
244 the high level of autonomy. A small amount of training will be required to qualify an
245 individual to repair/change the skin and retrieve samples.

246

247 2.4.12 **Maintenance**

248 2.4.12.1 **Lunar maintenance**: The skin of the LW will have to be removed and
249 cleaned/replaced every so many missions. The frequency of such maintenance
250 will be determined through testing.

251 2.4.12.2 **Earth Maintenance**: Parts shall be replaced as necessary with analysis for
252 future improvement.

253 3.0 **CLARIFICATIONS AND GUIDELINES**

254 N/A

255

256 4.0 **REVISIONS**

257 1.) CDD_Final (original)

258 2.) CDD_Final_RevA

259

260 5.0 **GLOSSARY**

261

262 This glossary defines every acronym in the document.

263 LA Tech – Louisiana Tech University

264 LW – Lunar Wormbot

265 UAH –University of Alabama in Huntsville

266

267 5.0 **REFERENCES**

268

269 [1] Dimensional specs based on documents provided by Blaze Sanders

Appendix B: Thermal Stress Analysis

Thermal Stress Analysis - Due to expansion of materials

+ This file analyzes the thermal expansion of the bulkhead and screw for earth and lunar conditions.

+ The stress created by this expansion is calculated and compared to the minimum tensile strength of the screw

Assumptions

- + Force from the expanding bulkhead is equally distributed between the three screws
- + 1/3 of the force of the expanding bulkhead is transferred completely to the screw's flange

Results

From the following calculations it was determined:

+ For earth conditions the screws can withstand the thermal expansion forces

+ For lunar conditions the screws CANNOT withstand the thermal expansion forces

Properties

$$l_{\text{alum}} := \frac{(6.875 - 6.375) \cdot \text{in}}{2} = 0.25 \cdot \text{in}$$

$$l_{\text{steel}} := 0.25 \text{in}$$

$$\alpha_{\text{alum}} := \frac{23.6 \cdot 10^{-6}}{\text{K}}$$

$$\alpha_{\text{steel}} := \frac{11.7 \cdot 10^{-6}}{\text{K}} \quad \begin{array}{l} \text{from mechanics of} \\ \text{materials 5th ed.} \\ \text{Beer} \end{array}$$

Area of screw's flange

$$\text{dia}_{\text{flange}} := 0.410 \cdot \text{in}$$

$$A_{\text{flange}} := \frac{\pi \cdot \text{dia}_{\text{flange}}^2}{4} = 8.518 \times 10^{-5} \text{m}^2$$

Minimum tensile strength

$$\text{max}_{\text{ts}} := 70000 \text{psi}$$

from mcmaster-car product description

Earth Conditions

Temperature change in system

$$dT := (537.11 - 531.67) \text{R} = 3.022 \text{K}$$

$$\alpha = \frac{dl}{l \cdot dT}$$

$$dl_{\text{alum}} := \alpha_{\text{alum}} \cdot l_{\text{alum}} \cdot dT = 1.783 \times 10^{-5} \cdot \text{in}$$

$$dl_{\text{steel}} := \alpha_{\text{steel}} \cdot l_{\text{steel}} \cdot dT = 8.84 \times 10^{-6} \cdot \text{in}$$

$$dl := dl_{\text{steel}} - dl_{\text{alum}}$$

$$dl = -8.991 \times 10^{-6} \cdot \text{in}$$

Since this is negative the bulkhead expands more than screw.

Therefore stress is created between the screw and bulkhead

Force exerted by expanding parts

Screw - Steel

$$\text{dia}_{\text{screw}} := 0.190 \cdot \text{in} \quad A_{\text{screw}} := \frac{\pi \cdot \text{dia}_{\text{screw}}^2}{4} = 1.829 \times 10^{-5} \cdot \text{m}^2$$

$$E_{\text{steel}} := 200 \cdot \text{GPa} \quad \text{from Mechanics of materials 5th ed. Beer}$$

$$F_{\text{screw}} := A_{\text{screw}} \cdot E_{\text{steel}} \cdot \alpha_{\text{steel}} \cdot dT = 129.362 \cdot \text{N}$$

$$\sigma_s := \frac{F_{\text{screw}}}{A_{\text{screw}}} = 1.026 \times 10^3 \cdot \text{psi} \quad \text{Stress from expanding screw}$$

Bulkhead - Aluminum

$$\text{dia}_{\text{bh}} := 4 \cdot \text{in} \quad A_{\text{bh}} := \frac{\pi \cdot \text{dia}_{\text{bh}}^2}{4} = 12.566 \cdot \text{in}^2$$

$$E_{\text{al}} := 72 \cdot \text{GPa} \quad \text{from Mechanics of materials 5th ed. Beer}$$

$$F_{\text{bh.total}} := A_{\text{bh}} \cdot E_{\text{al}} \cdot \alpha_{\text{alum}} \cdot dT = 4.163 \times 10^4 \cdot \text{N}$$

$$F_{\text{bh}} := \frac{F_{\text{bh.total}}}{3} = 1.388 \times 10^4 \cdot \text{N}$$

Total force is divided between 3 screws in bulkhead

$$\sigma_{\text{bh}} := \frac{F_{\text{bh}}}{A_{\text{flange}} - A_{\text{screw}}} = 3.009 \times 10^4 \cdot \text{psi}$$

Stress from expanding bulkhead

Total Stress

$$\sigma_{\text{total}} := \sigma_s + \sigma_{\text{bh}} = 3.112 \times 10^4 \cdot \text{psi} \quad \max_{\text{ts}} = 7 \times 10^4 \cdot \text{psi}$$

Total stress is less than max tensile strength of screw

$$\max_{\text{ts}} - \sigma_{\text{total}} = 3.888 \times 10^4 \cdot \text{psi}$$

Lunar Conditions

Temperature change in system

$$dT_{lu} := (435.668 - 256)K = 179.668 K$$

$$\alpha = \frac{dl}{l \cdot dT}$$

$$dl_{alum_lu} := \alpha_{alum} \cdot l_{alum} \cdot dT_{lu} = 1.06 \times 10^{-3} \cdot \text{in}$$

$$dl_{steel_lu} := \alpha_{steel} \cdot l_{steel} \cdot dT_{lu} = 5.255 \times 10^{-4} \cdot \text{in}$$

$$dl_{lu} := dl_{steel_lu} - dl_{alum_lu}$$

$$dl_{lu} = -5.345 \times 10^{-4} \cdot \text{in}$$

Since this is negative the bulkhead expands more than screw.
Therefore stress is created between the screw and bulkhead

Force exerted by expanding parts

Screw - Steel

$$dia_{screw} := 0.190 \cdot \text{in} \quad A_{screw} := \frac{\pi \cdot dia_{screw}^2}{4} = 1.829 \times 10^{-5} \text{ m}^2$$

$$E_{steel} := 200 \cdot \text{GPa}$$

from Mechanics of
materials 5th ed.
Beer

$$F_{screw_lu} := A_{screw} \cdot E_{steel} \cdot \alpha_{steel} \cdot dT_{lu} = 7.69 \times 10^3 \cdot \text{N}$$

$$\sigma_{s_lu} := \frac{F_{screw_lu}}{A_{screw}} = 6.098 \times 10^4 \cdot \text{psi} \quad \text{Stress from expanding screw}$$

Bulkhead - Aluminum

$$dia_{bh} := 4 \text{ in} \quad A_{bh} := \frac{\pi \cdot dia_{bh}^2}{4} = 12.566 \cdot \text{in}^2$$

$$E_{al} := 72 \cdot \text{GPa}$$

from Mechanics of
materials 5th ed.
Beer

$$F_{bh.total_lu} := A_{bh} \cdot E_{al} \cdot \alpha_{alum} \cdot dT_{lu} = 2.475 \times 10^6 \text{ N}$$

$$F_{bh_lu} := \frac{F_{bh.total_lu}}{3} = 8.25 \times 10^5 \text{ N}$$

Total force is divided between 3 screws in
bulkhead

$$\sigma_{bh_lu} := \frac{F_{bh_lu}}{A_{flange} - A_{screw}} = 1.789 \times 10^6 \cdot \text{psi}$$

Stress from expanding bulkhead

Total Stress

$$\sigma_{\text{total_lu}} := \sigma_{s_lu} + \sigma_{bh_lu} = 1.85 \times 10^6 \cdot \text{psi} \quad \max_{ts} = 7 \times 10^4 \cdot \text{psi}$$

Total stress is MORE
than max tensile
strength of screw

$$\max_{ts} - \sigma_{\text{total_lu}} = -1.78 \times 10^6 \cdot \text{psi}$$

Appendix C: Heat Dissipation Analysis

Thermal Analysis:

Key Assumptions:

- 1) Uniform Temperature Distribution
- 2) Vertical Cylinder in Semi-Infinite Medium
- 3) 85% component efficiency
- 4) Steady State

$$eL := (6.705)\text{in} \quad D := 4\text{in} \quad S_f := \frac{2\pi \cdot eL}{\ln\left(4 \frac{eL}{D}\right)} \quad T_{\text{inf}} := 72^\circ\text{F} = 295.372\text{K}$$

$$t := .041\text{in} \quad r_2 := \frac{D}{2} \quad r_1 := r_2 - t \quad q_{\text{system}} := (7.147\text{W}) \cdot 15\%$$

$$k_{\text{leather}} := 0.14 \frac{\text{W}}{\text{m}\cdot\text{K}} \quad k_{\text{sand}} := 0.20 \frac{\text{W}}{\text{m}\cdot\text{K}} \quad k_{\text{regolith}} := 1.5 \cdot 10^{-4} \frac{\text{W}}{\text{cm}\cdot\text{K}}$$

Sand Bed

$$T_s := \frac{q_{\text{system}}}{S_f \cdot k_{\text{sand}}} + T_{\text{inf}} = 304.904\text{K}$$

$$T_{\text{ie}} := \frac{q_{\text{system}} \cdot \ln\left(\frac{r_2}{r_1}\right)}{2\pi \cdot k_{\text{leather}} \cdot eL} + T_s = 31.902^\circ\text{C}$$

Lunar Regolith

$$T_{\text{inf}} := 256\text{K} \quad T_{\text{sRegolith}} := \frac{q_{\text{system}}}{S_f \cdot k_{\text{regolith}}} + T_{\text{inf}}$$

$$T_{\text{iL}} := \frac{q_{\text{system}} \cdot \ln\left(\frac{r_2}{r_1}\right)}{2\pi \cdot k_{\text{leather}} \cdot eL} + T_{\text{sRegolith}} = 110.09^\circ\text{C}$$

Appendix D: Force and Efficiency Analysis

Force and Power Consumption Analysis

Sidewall Member Material Properties:

$$E := 1.1 \cdot 10^6 \cdot \text{psi} \quad \text{Approximation for fiberglass}$$

Sidewall member dimensions:

$$b := 1 \cdot \text{in} \quad h := .041 \cdot \text{in} \quad L := 6.5 \cdot \text{in} = 0.165 \text{ m}$$

Dimensions of Segment:

$$D := 4 \text{ in}$$

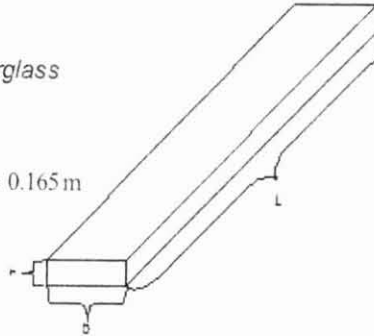
Number of Sidewall members per segment:

$$N_s := \frac{\pi \cdot D}{b}$$

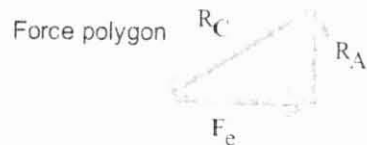
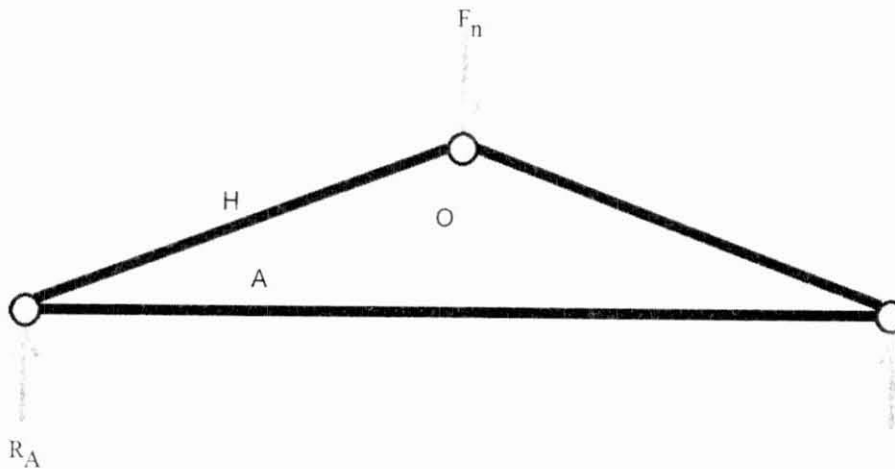
Normal force required:

$$F_{n_total} := 66 \cdot \text{N}$$

$$F_n := \frac{F_{n_total}}{N_s} = 1.181 \cdot \text{lbf}$$



Truss estimation of sidewall forces:



ActuatorInitialLength := 6.3·in

$$H := \frac{L}{2} \quad A := \frac{(\text{ActuatorInitialLength})}{2} = 3.15 \cdot \text{in}$$

Reaction Forces:

$$R_A := \frac{F_n}{2} \quad O := .65 \text{in}$$

Starting Guesses: $R_C := 10 \cdot \text{lbf}$ $F_e := R_C$

Solve Block

Given

$$F_e - R_C \cdot \left(\frac{A}{H} \right) = 0$$

$$R_A - R_C \cdot \left(\frac{O}{H} \right) = 0$$

$$\begin{pmatrix} F_e \\ R_C \end{pmatrix} := \text{Find } F_e, R_C = \begin{pmatrix} 2.861 \\ 2.952 \end{pmatrix} \cdot \text{lbf}$$

Column Buckling:

$$I := \frac{1}{12} \cdot b \cdot h^3$$

$$P_{cr} := \frac{\pi^2 \cdot E \cdot I}{L^2} = 1.476 \cdot \text{lbf}$$

Total Force Exerted by Linear Actuators:

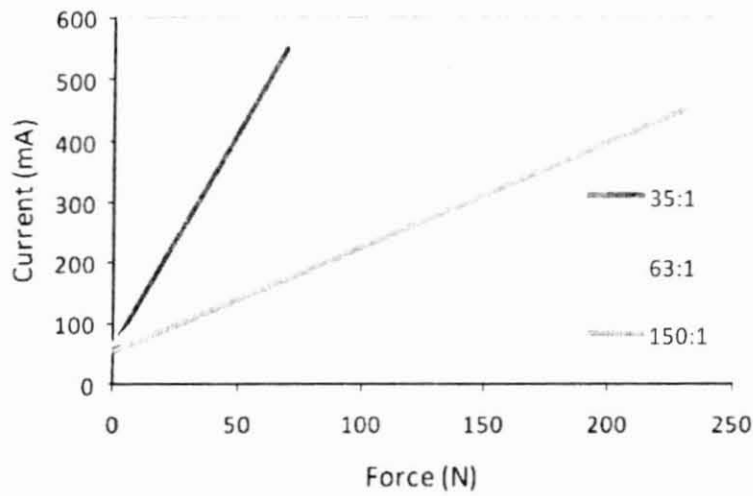
$$\text{TotalForce} := F_e + P_{cr} \cdot N_s = 54.498 \cdot \text{lbf}$$

$$\text{TotalForce} = 242.419 \text{N}$$

$$F_{\text{strip}} := F_e + P_{cr} = 4.337 \cdot \text{lbf}$$

$$\text{Eff} := \frac{F_n}{F_{\text{strip}}} \cdot 100 = 27.226$$

Current Curves



Current Plot provided with Firgelli L16 Datasheet

Power Consumption of One Active Segment using 3) L16 actuators:

Curve Fit of 150:1 Actuator:

$$I(F) := F \cdot \frac{(400 \cdot \text{mA} - 100 \cdot \text{mA})}{200 \cdot \text{N} - 25 \cdot \text{N}} + 60 \cdot \text{mA}$$

$$I\left(\frac{\text{TotalForce}}{3}\right) = 0.199 \text{ A}$$

$$V := 12 \cdot \text{V}$$

$$P := I\left(\frac{\text{TotalForce}}{3}\right) \cdot V \cdot 3 = 7.147 \text{ W}$$

$$\frac{P}{3} = 2.382 \text{ W}$$

Appendix E: Product Design Specifications (PDS)

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Product Design Specification
Lunar Wormbot Project

Prepared by
MAE 491/492 Project Office
The University of Alabama in Huntsville
Huntsville, AL

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This Product Design Specification is developed for use in a class at the University of Alabama in Huntsville and does not contact a legal agreement or imply direction to perform work by a Government Agency.

Revision--

22 **Product Design Specification Approval**

23 The undersigned agree that the attached Product Design Specification as marked
24 describes the product/prototype specifications for the MAE 491/492 Class Project. From
25 this time forward, any questions, clarifications or changes concerning the Product
26 Design Specification shall be submitted in writing through the MAE 491/492 Instructor to
27 the Customer Representative and the answer distributed to all MAE 491/492 participants
28 in writing.

29
30 To change the Product Design Specification after signatures are completed shall require
31 that the change be stated in writing and that a person authorized by every one of the
32 signers below endorse the change with their signature. The revision will be labeled
33 uniquely and distributed to all participants simultaneously.

34
35 The original of this document will be kept on file with the UAH Instructor. All signers will
36 receive a copy of the original document.

37
38 _____ / _____
39 Blaze Sanders, Customer Representative/ Technical Advisor, NASA

40
41 _____ / _____
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63
64
65 _____ / _____
66 Dr. Christina Carmen, MAE 491/492 Instructor

67

Revision--

68

69

70 1. **SCOPE:** This specification establishes the purpose, functional requirements,
71 corporate constraints and social, political and legal requirements for the Lunar Wombot
72 Project. The mission of the Lunar Wombot (LW) Project is to design a prototype of a
73 robotic burrowing worm in order to prove the concept on Earth using a lunar regolith
74 simulant. The LW consists of a piezoelectric ultrasonic drill, a conical auger, and
75 multiple elongating segments mimicking the peristaltic motion of an earthworm. One key
76 function of the LW is to retrieve lunar samples taken from various depths within the lunar
77 surface, for either in-situ analysis or for return to Earth. The drill bit will both loosen the
78 regolith and fracture large rocks encountered. An auger will displace the regolith,
79 facilitating the robot's ability to tunnel. The multiple segments of the LW will allow
80 movement in a specified direction by providing a preload force for the drill and auger as
81 well as assisting in the displacement of regolith.

82 2. **CUSTOMER AND MARKET SURVEY REQUIREMENTS** The Lunar Wombot is
83 described in terms of its initial requirements and constraints as dictated by the customer
84 and the market survey.

85 2.1 Requirement 1. The LW shall be capable of burrowing through fine particulate
86 matter.

87 2.2 Requirement 2. The LW shall implement peristaltic locomotion allowing one-
88 dimensional burrowing, and should have segments articulated in three
89 dimensions.

90 2.3 Requirement 3. The LW concept shall be designed for Earth based testing.

91 2.4 Requirement 4: The LW shall be capable of taking 50 one gram samples at
92 various depths.

93 2.5 Requirement 5: The LW shall be capable of utilizing a power source supplying
94 20 Watts peak power per segment.

95 2.6 Requirement 6: The LW shall incorporate an ultrasonic drill bit and auger in the
96 head section.

97 2.7 Requirement 7: The LW shall use an elastic, water-tight skin material capable of
98 insulating internal electrical and mechanical systems from fine particulate
99 matter.

100 2.8 Requirement 8: The LW shall have space to integrate a sensing and navigation
101 package.

102 2.9 Requirement 9: The LW should be capable of returning to the surface with all
103 acquired samples.

Revision--

- 104 2.10 Requirement 10: The LW should apply mechanical force by means of motors or
105 actuators situated perpendicular to its longitudinal axis.
- 106 2.11 Requirement 11: The LW design should be optimized using X-TOOLSS
107 software.
- 108 2.12 Requirement 12: The LW shall be analyzed using modeling and simulation
109 techniques prior to prototype testing.
- 110 2.13 Requirement 13: The LW auger shall be designed to optimize soil displacement
111 and forward motion.
- 112 2.14 Requirement 14: Individual dummy segments shall be between 50% and 90%
113 of locomotion segment volume.
- 114 2.15 Requirement 15: The LW should avoid using consumable mass (i.e.
115 compressed inert gas vented from the machine).
- 116 2.16 Requirement 16: The LW shall produce at least 66 N of force directed
117 perpendicular to the segment's longitudinal axis at the center hinge.
- 118 2.17 Requirement 17: The LW should withstand temperature extremes on the lunar
119 surface.

120 3. MAJOR COMPONENT LIST

121 The Lunar Wormbot will consist of three major assemblies, of which two will be
122 considered by Team 1 for design and implementation. These three are the Body, Head,
123 and Surface Support structure. Due to the relative separateness of the Surface Support
124 structure, it will be viewed as its own major system to be developed once the viability of
125 the wormbot system has been proven. Hence, only the Body and Head will be
126 considered in detail with the Surface Support structure generally described to outline
127 important features.

128 3.1 **Head**: The head shall be the foremost portion of the wormbot. It will be the
129 primary drilling and regolith moving portion.

130 3.1.1 **Auger**: The auger shall have a conical shape to displace the regolith to the
131 sides of the wormbot. Also, it will have an optimized logarithmic screw
132 thread to further displace regolith and encourage forward motion.

133 3.1.2 **Ultrasonic Drill**: A drill capable of breaking up larger, harder objects in the
134 regolith will be located on the foremost point of the head.

135 3.1.3 **Motor**: A rotary motor shall drive both the Auger and drill.

Revision--

136 3.1.4 **Sensing Package:** Additional space should be incorporated into the head to
137 allow for future addition of a computing brain and sensing package.

138 3.2 **Body:** The body shall comprise the majority of the wormbot's volume and length
139 and will be segmented in design. It shall be comprised of Active Segments and
140 Dummy Segments. A composite Skin shall comprise the third major component
141 of the Body.

142 3.2.1 **Active Segments:** Active Segments will provide the forward motive force via
143 sequenced contraction and expansion resulting in peristaltic motion. At
144 minimum, the Active Segments will be comprised of:

145 **Actuators:** The Actuators will expand and contract the segment to
146 produce a forward force and a normal force on the walls of the burrow.

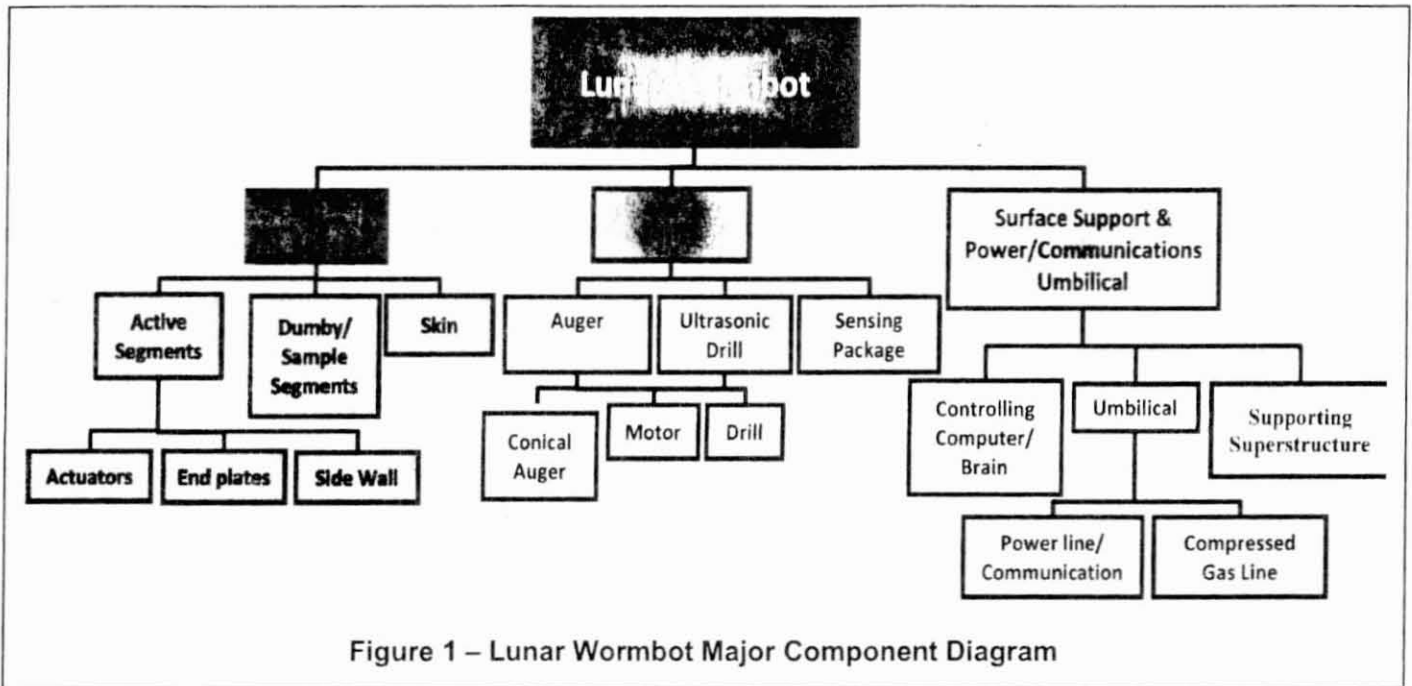
147 **End Plates:** A pair of end plates will divide one segment from another
148 and provide the coupling system to join one segment to the next.

149 **Side Wall:** The outer wall of the segment will be the member through
150 which the force is directed outward and into the soil of which it is to
151 burrow. Thus it must be constructed of either a springy, durable material
152 or of hinged plates.

153 3.2.2 **Dummy/Sampling Segments:** Dummy segments will not play an active role
154 in the movement of the wormbot. Their mission purpose is to gather regolith
155 samples during the wormbot's descent and retain them for collection upon
156 return to the surface.

157 3.2.3 **Skin:** Due to the very fine and abrasive nature of regolith, the skin will need
158 to be very tough and abrasion resistant, flexible, and as nearly impervious
159 to fine dust as possible.

160 3.3 **Surface Support Structure:** A support structure will be located on the lunar
161 surface. This structure will house the main computing and communications
162 brain of the wormbot, supply power, and potentially provide some consumables
163 such as compressed gas via a tethered umbilical.



164

165 4. PURPOSE AND MARKET FOR PRODUCT

166 4.1 Product Name: Lunar Wormbot

167 4.2 Product Purpose and Function it is to Perform: The program goal is to lead to
 168 knowledge enabling a burrowing robot to operate on the lunar surface to gather
 169 soil samples. Leading to that goal, and staying within the scope of the time period
 170 of this project, a single, prototype LW will be produced for earth based testing.
 171 This robot will be considered successful in its mission if it offers the ability to
 172 burrow through a fine particulate soil simulant, return testing data leading to
 173 improvements in design, and exhibits the robustness necessary for space based
 174 soil sampling.

175 4.3 Predictable Unintended Uses of Product:

176 4.3.1 Commercial Applications

177 Rescue Operations

178 Telecommunications

179 Mineral/Resource Exploration

180 Pollution Detection

181

182 **4.3.2 Military Applications**

183 Explosive Delivery

184 Intelligence

185 Mine Detection

186 **4.3.3 Planetary Exploration Applications**

187 **4.4 Product Special Features:**

188 **4.4.1 Drilling Features**

189 Ultrasonic Drill

190 Logarithmic Auger

191 **4.4.2 Motion Control Features**

192 To be determined

193 **4.4.3 Sampling Mechanisms**

194 To be determined

195 **4.5 Intended Market, Need, Demand:**

196 **4.5.1 Intended Market:** NASA/NSSTC

197 **4.5.2 Market Need:** One prototype.

198 **4.5.3 Market Demand:** No current market demand beyond one prototype.

199 **4.6 Company Selling Price/Estimated Retail Price:**

200 **4.6.1 Cost Analysis:** To be determined

201 **4.7 Product Competition:**

202 **4.7.1 Conventional Approaches**

203 **5. FUNCTIONAL REQUIREMENTS**

204 **5.1 Functional Performance:**

Revision--

205 5.1.1 **Power Flow:** The surface support structure shall provide all power through
206 a tether system to the LW. Power is applied through a bus to each locomotive
207 segment, the ultrasonic drill bit and auger.

208 5.1.2 **Flow of Information:** The central processing unit will be located on the aft
209 end of the LW. Each segment will use a microprocessor to control the
210 actuators and allow feedback to the central processing unit. Space shall be left
211 for additional navigational and informational systems.

212 5.1.3 **Material Functional Performance:** The LW shall be able to withstand
213 axial and transverse forces to allow full functional performance.

214 5.1.4 **Operational Steps:** To allow worm like motion, the machine uses a
215 peristaltic algorithm for locomotion. The general process is that all power is
216 transmitted to the auger to break up and transport regolith behind the head
217 section. All segments are in an off and locked position to facilitate maximum
218 power consumption for the auger. Next, linear actuators at the rear of the LW
219 are used to force the radius of the machine to expand at that section. Position
220 sensors on the actuators themselves give an accurate depiction of segment
221 alignment, ± 5 mm, and the position is locked internally by the actuators. The
222 foremost segment is then expanded to set the head position, and the
223 expansion process moves rearward, applying preload forces to the auger and
224 ultrasonic bit.

225 5.1.5 **Product Efficiency:** Testing will determine product efficiency.

226 5.1.6 **Product Accuracy:** Testing will determine product accuracy.

227 **5.2 Physical Requirements:**

228 5.2.1 **Size:** The LW segment contracted size is roughly 7.5 inches in diameter
229 and 3.5 inches in length. Expanded segments will be 4 inches in diameter and
230 5.5 inches in length. Overall length of the extended body with 8 locomotive
231 segments is 44 inches.

232 5.2.2 **Weight:** The LW individual segment will weigh approximately 2-3 pounds.
233 The LW body section will weigh approximately 16-24 pounds.

234 5.2.3 **Materials:** The LW will be comprised of an aluminum framework with a
235 composite skin made of fiberglass epoxy.

236 5.2.4 **Skin:** Glass fibers are combined with a resin in a bilateral weave shaped in
237 a tubular fashion positioned between bulkheads.

238 5.2.5 **Processing:** A microcontroller, switch, and ADC are utilized in each
239 segment and an Arduino microcontroller for main processing.

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240 **5.3 Service Environment:** The end machine will be used to demonstrate proof of
241 concept in a regolith stimulant, flour, or dry concrete mix. The simulating
242 environment will need to range in compaction from sifted to full compaction to
243 simulate the range of regolith densities the machine will experience.

244

245 **5.4 Life-Cycle Issues:**

246 5.4.1 **Reliability:** Linear actuators are rated to 20,000 strokes, with a
247 temperature range of -10C to 50C. Arduino boards are capable of operation in
248 -40C to 85C.

249 5.4.2 **Failure:** Most probable failure modes are particle intrusion due to skin
250 failure, auger motor fatigue, and communications and power line severance.

251 5.4.3 **Maintainability:** Due to the LW's geometry, all parts will be accessible and
252 can be easily replaced or upgraded.

253 5.4.4 **Diagnosability:** Due to the small number of parts, failures will be easy to
254 diagnose. Additionally, active components (i.e. linear actuators) provide
255 feedback.

256 5.4.5 **Testability:** The LW will be able to withstand numerous testing conditions
257 to be determined at a later date.

258 5.4.6 **Reparability:** Focus on skin repair procedures will determine the overall
259 reparability of the product.

260 5.4.7 **Installability:** N/A

261 5.4.8 **Retirement from Service:** Product life will end when testing evaluation
262 yields sufficient results.

263 5.4.9 **Recyclability:** The majority of components are of metallic nature and can
264 be recycled utilizing conventional methods.

265 5.4.10 **Cost of operation:** Cost will be associated with storage, maintenance,
266 transportation, testing apparatus, and test personnel.

267 **5.5 Human Factors:**

268 5.5.1 **Aesthetics:** N/A

269 5.5.2 **Maintenance:** Due to the LW's geometry, all parts will be accessible and
270 can be easily replaced or upgraded.

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271 5.5.3 **User Training:** End users will need to be familiar with basic robotics and
272 programming capabilities for full usability.

273 **5.6 Facilities, Transportation and Storage:**

274 5.6.1 **Facilities:** The LW construction can be done in a standard machine shop.
275 The auger will need either Rapid prototyping or 5-axis machining to get the
276 desired logarithmic spiral. Support facilities for this project should be minimal. A
277 testing area and a laptop will suffice for testing purposes.

278 5.6.2 **Transportation:** The LW shall be small enough to fit into the back of most
279 cars. Under current concepts it will be at least a 2 person lift. It is
280 recommended that a cart is used for room-to-room transportation.

281 5.6.3 **Storage:** The LW shall be stored in standard room conditions while not
282 being tested.

283

284 **6. CORPORATE CONSTRAINTS**

285 **6.1 Time to Market:**

286 **Design Time:** 3-4 months

287 **Manufacture Time:** 2-3 months

288 **Test Product Time:** 1 month

289

290 **6.2 Manufacturing Requirements:** The LW construction will be done in a standard
291 machine shop. The auger will need either Rapid prototyping or 5-axis machining
292 to get the desired logarithmic spiral. Support facilities for this project should be
293 minimal. A testing area and a laptop will suffice for testing purposes.

294

295 **6.3 Suppliers:**

296 6.3.1 **Linear Actuators:** firgelli.com – readily available

297 6.3.2 **Bulkheads and Brackets:** onlinemetals.com – readily available

298 6.3.3 **Skin:** uscomposites.com – readily available

299

300 **6.4 Trademark, Logo, Brand Name:** No known conflicts.

301

302 **6.5 Financial Performance:** Depending on testing evaluation, the LW may be
303 profitable in few commercial markets and provide support for government
304 contracts.

305

306 **6.6 Corporate Ethics:** To be determined

307

308 **6.7 Budget:** To be determined

309 7. SOCIAL, POLITICAL AND LEGAL REQUIREMENTS

310
311 7.1 Safety and Environmental Regulations:

312 7.1.1 **Safety Regulations:** Manufacturing and mission processes shall be
313 performed in accordance with OSHA standards.

314 7.1.2 **End of product life disposal:** Hazardous material shall be disposed of in
315 a manner to be determined by local waste management.

316
317 7.2 Standards: To be determined

318

319

320

321

322 7.3 Safety and Product Liability: Warning labels shall be placed on areas of the
323 product where a high probability of injury may occur. This includes but is not
324 limited to pinch points, electrical hazards, and sharp edges. Warning labels
325 should not be placed in any area in which the function of the product is deterred
326 or may cause the labels to be worn off.

327

328 7.4 Patents and Intellectual Property:

329

330 7.4.1 **Patented Parts:** To be determined

331

332 7.4.2 **Similar Patented Products:** None are known at the present time.

333

334 7.4.3 **Intellectual Property:** To be determined

335

336 7.4.4 **Infringement Avoidance:** To be determined

337 8. **Glossary**

338

339 This glossary defines every acronym in the document.

340

341 LW – Lunar Wormbot

342 PDS – Product Design Specification

343 UAH –University of Alabama in Huntsville

344

345 9. **References**

346 N/A

347