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DESIGN AND DEVELOPMENT OF A GROUND BASED ROBOTIC TUNNELLING WORM FOR OPERATION IN HARSH ENVIRONMENTS

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The United States (US) National Aeronautics and Space Administration (NASA) Apollo program missions to the moon, which concluded almost 40 years ago, allowed for the retrieval of lunar soil otherwise known as lunar regolith. However, the diversity of the samples acquired was limited due to the logistical inability of the astronauts to penetrate the moon's surface to a depth greater than 3 meters. In order to achieve a broader knowledge of lunar regolith and its changing nature at various depths, future lunar missions will require the implementation of tools that possess the ability to burrow at various depths and collect samples for subsequent analysis. Furthermore, the elimination of human interaction during the long and strenuous coring process would enable astronauts to concentrate on higher level tasks. To penetrate the 3 meter barrier, a collaborative design effort encompassing teams from the University of Alabama in Huntsville (UAH), Louisiana Tech University (LA Tech), the University of California in Riverside (UCR), Johns Hopkins University (JHU), NASA's Marshall Space Flight Center (MSFC) and the National Space Science and Technology Center (NSSTC) has resulted in the design, analysis, modelling, fabrication and testing a lunar regolith burrowing device – referred to as the Lunar Wormbot (LW). The current article is a ground based development unit designed to replicate the peristaltic motion of an earthworm. The UAH Mechanical and Aerospace Engineering (MAE) design team was comprised of undergraduate students charged with the task of designing and fabricating the robotic body segments of the LW. The UAH team worked in parallel with other undergraduate design teams at LA Tech and UCR. NASA engineers and scientists from the NSSTC, JHU, and MSFC acted as technical advisors for the student teams. The UAH student design team employed the NASA Systems Engineering (SE) handbook as a guide throughout the design and implementation phases. The UAH team has performed extensive technical analyses including the evaluation of structural load conditions, thermal stresses, material stresses and deflections, and operational reliability. The presented paper provides an overview of the LW design with an emphasis upon the UAH efforts in association with the design, analysis, modelling, fabrication and testing of the LW body.

I. BACKGROUND

The idea of the Lunar Wormbot (LW) was first presented to students attending the NASA Robotics Academy (RA) at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama in the summer of 2010. The team, consisting of members from the University of Maryland-College Park, Johns Hopkins University (JHU), and Embry-Riddle Aeronautical University, was given a short period of time to conceptualize and manufacture a prototype of the LW. Their design, as shown in Figure I, resulted in a robot consisting of a conical auger with a piezoelectric ultrasonic drill and multiple elongating segments to mimic the peristaltic motion of an earthworm. The ultrasonic drill proposed would pulverize any hard rock or compacted minerals into loose soil. This soil would then be displaced to the body segments by a conical

Fig I: Robotics Academy Lunar Wormbot Concept [1]

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Fig. II: Conical auger prototype [1]

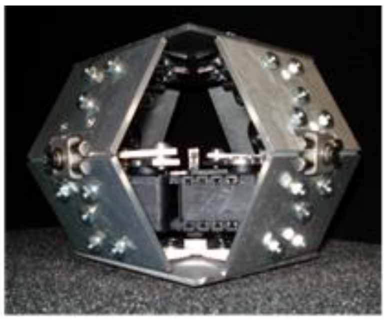


Fig. III: Robotics Academy prototype of a LW body segment [1]

auger. Body segments would also aid in the displacement of the soil and allow motion. Within the collection of body segments, it was proposed that one segment, referred to as a dummy segment, would have the ability to collect soil samples at any given depth.

The efforts of the (RA) team resulted in a prototype of the conical auger, as shown in Figure II, and a prototype of a body segment, shown in Figure III. Manufactured via rapid prototyping, the acrylonitrile butadiene styrene (ABS) plastic auger was tested in a bed of flour to capture the design's ability to displace material. The body segment utilized hinged plates with a servo and piston design.

At the conclusion of the 2010 NASA Robotics Academy, the LW concept was provided to a University of Alabama in Huntsville (UAH) senior design class to evaluate and propose an alternative design to realize the LW concept. The UAH team was given two semesters to accomplish a similar goal of the Robotics Academy team- design and manufacture a prototype of the LW. With acting advisors from NASA engineers and scientists from the NSSTC, JHU, and MSFC, it was decided that the student design team would focus on the body segments of the LW. The auger and soil acquisition system were given to the Louisiana Tech University (LA Tech) and the University of California in Riverside (UCR) to develop.

II. SYSTEM OVERVIEW

A primary objective of the UAH team was to utilize the NASA Systems Engineering Handbook and implement the NASA Systems Engineering Engine [2]. Shown below in Figure IV 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

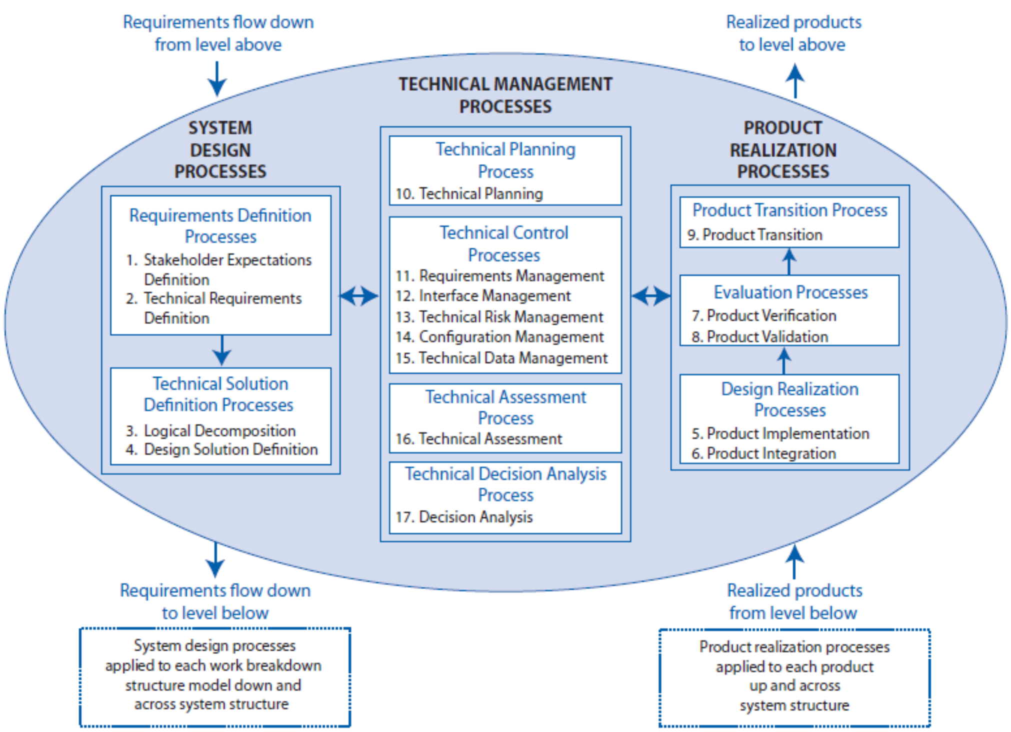


Fig. IV: The NASA systems engineering engine [2] customers and locally interested professionals. The reviews conducted to date include the following: System Requirements Review (SRR), Conceptual Design Review (ConDR), Preliminary Design Review (PDR), and Critical Design Review (CDR). The purpose of the 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.

II.I. System Requirements

The UAH team was briefed with general requirements for the mission by advisors. 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.

A Concept Description Document (CDD) was created to provide the requirements for the mission. The project requirements definition was a collaborative effort between the UAH team and the advisors. 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. Due to the cost of materials necessary to operate on a lunar surface, it was decided that the prototype would be limited to operating in earth conditions while keeping in mind future adaptations for space and commercial operations.

The major requirements of the project listed in the CDD were 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.

II.II. Patents and Research

Forty-four patents for boring implements were reviewed in depth. While no patented machines were influential, some experimental devices shared common features with the RA's original LW design. An experimental device (Figure V), developed by Chuo University in Japan, utilizes several mechanical functions desired by the Lunar Wormbot team [3]. 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.

Fig. V: Chuo University's Wormbot prototype [3]

The Lunar Wormbot will, however, carry and make use of an ultrasonic drill similar to the one described in US patent number 6863136 (Figure VI). 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 [4]. This implement requires a very low preload force, 10 Newtons, and is capable of coring glassy mineral formations.

The team researched various properties of lunar soils, and specifically lunar regolith. Apollo program research details the particulate composition of the regolith, as well as probable compaction details.

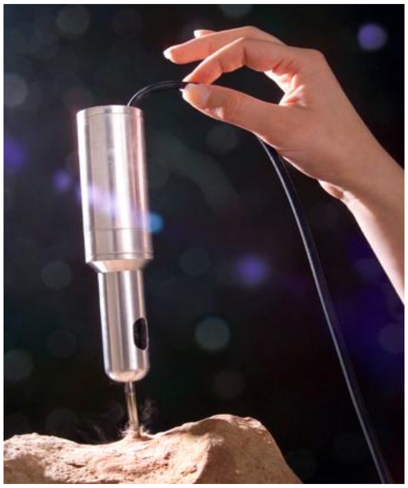


Fig. VI: Ultrasonic drill patent number 6863136 [4]

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 VII, 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 [5]. The regolith layer extends roughly ten meters below the surface, followed by large scale ejecta [6].

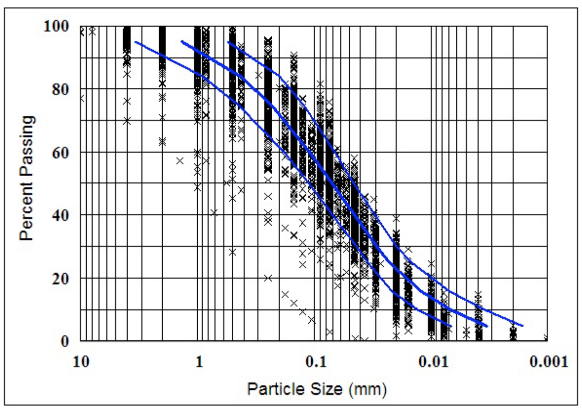


Fig. VII: Lunar regolith particle size [7]

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 [6]. 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 [8].

II.III. Conceptualization

During the design phase, several locomotive segment concepts were considered and analyzed. The RA's concept of the LW uses four AX-12 servo motors per segment to spin a three bar linkage which pushes on the sidewall causing it to expand outward. 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.

From the RA's original design, the UAH design team produced a variant of the design using linear actuators in place of the AX-12 servo motors as shown in Figure VIII. This design compared to the original was less complex, more powerful, and had fewer failure modes due to fewer moving parts.

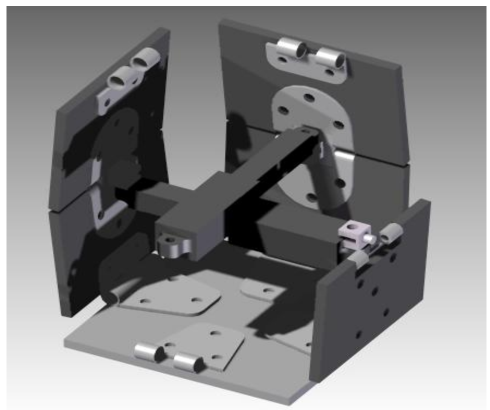


Fig. VIII: UAH variant of RA design using linear actuators

Two additional concepts considered by the UAH team share the same basic internal structure, as shown in Figure IX. 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,

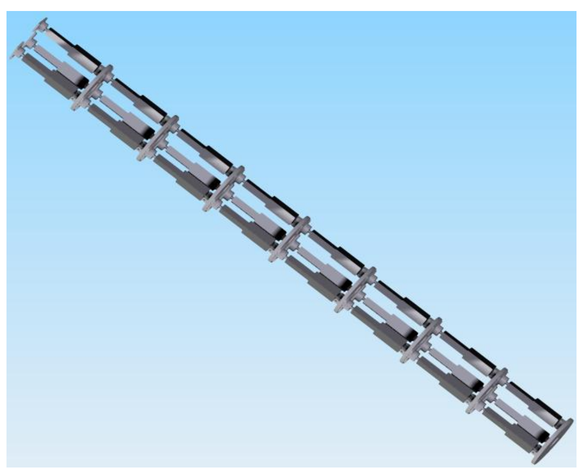


Fig. IX: Skeletal structure of LW concept providing a normal force between the LW and the burrowed tunnel wall, allowing for peristaltic motion. The main difference between the two concepts is that one uses a flexible wall which is pressurized internally, and the other uses a spring wall. The flexible wall would have required the LW to be fed a consumable gas from an above surface support structure via a tether. The spring wall concept uses a material capable of elastic deformation as the linear actuators compress. Also, the latter concept utilizes a leather skin to sheathe the entire locomotive segments. The leather is used to prevent any particulate intrusion that may lead to mechanical failure.

After carefully analyzing the aforementioned concepts, the UAH team decided to pursue the development of the spring wall concept. 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 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. 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.

III. PRELIMINARY DESIGN

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, in each segment. A plastic wiring bus conduit is clamped to the center of the two bulkheads in the lateral axis of the segment.

III.I. Materials 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.

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.

III.II. Technical Analyses

Several different types of analysis were performed on various components of the body segment system. From Finite Element Analysis, material, thermal, and force analysis, these analyses resulted in the authority to proceed in procuring the necessary materials for the prototype.

III.II.I. Finite Element Analysis

The finite element 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 X) and the deflection (Figure XI).

From this analysis, it was determined that the maximum stress experienced by the bulk head is 3.35x104 psi, and the max deflection is 1.79x10-3 in. This yields a factor of safety of 298 which is extremely high; this has not been optimized yet because of the

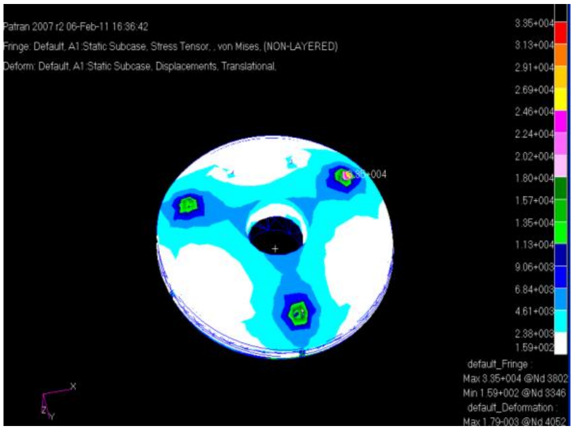


Fig. X: Stress tensor of aluminum bulkhead

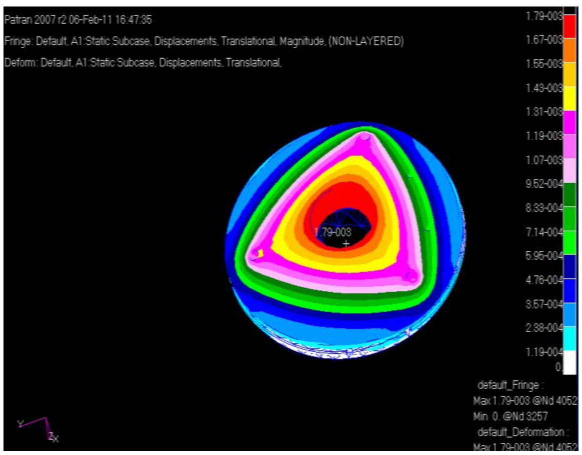


Fig. XI: Deflection of aluminum bulkhead

project's 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.

III.II.II. Thermal 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 modelled 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.

A thermal analysis was also 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 [9].

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:

$$S = \frac{2\pi L}{\ln(4L/D)} \quad [1]$$

$$q = Sk(T_s - T_{inf}) \quad [2]$$

$$q = \frac{2\pi Lk(T_i - T_s)}{\ln(r_2/r_1)} \quad [3]$$

[1] shape factor for a vertical cylinder in a semi-infinite medium
[2] heat transfer by conduction using a shape factor
[3] 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 I, indicate the maximum internal temperature of the LW in each test material. Table II provides the maximum allowable temperatures of each component of an individual LW segment.

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

Table I: LW body segment internal 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

Table II: Material specific maximum allowable temperature

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. It should also be noted that upgrades to the actuators and slave boards are the key elements selected for future work as proposed in section VII.

III.II. III. Force and Efficiency Analysis

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 XII.

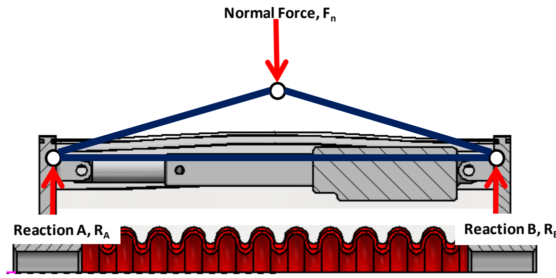


Fig. XII: Simplified force analysis model

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 Firgelli'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 advisors were met.

IV. FINAL DESIGN

IV.I. Design Overview

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 XIII). Upon closer

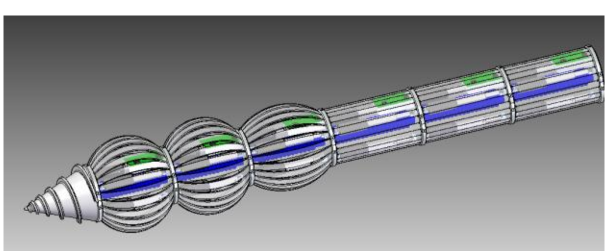
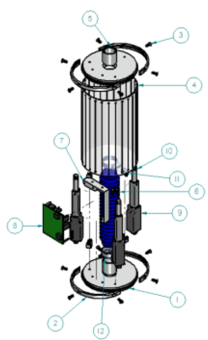


Fig. XIII: Lunar Wormbot assembly

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 XIV) 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 and aluminum mounting bracket that both grounds the electronics and allows heat dissipation into the body of the LW.



Item Number	Document Number	Title	Material	Quantity
1	LW2011_1	Bulkhead	Aluminum 7075-T6	2
2	LW2011_7	Lock Ring	Aluminum 7075-T6	4
3	92210A127	Lock Ring Screw - 92210A127	Stainless steel	12
4	LW2011_4	Sidewall Members	Fiberglass	1
5	LW2011_3	Conduit Connection	Aluminum 7075-T6	2
6	LW2011_2	Central Conduit	PTFE	1
7	LW2011_9	Electronics Mounting Bracket	Aluminum 7075-T6	1
8	LW2011_10	Electronics - Slave Board	Printed Circuit Board	1
9	LW2011_6	L16 Actuator Body		3
10	LW2011_7	L16 Extender Rod		3
11	LW2011_8	Actuator Mount	Steel	6
12	LW2011_5	Hose Clamp	Stainless steel	2

Fig. XIV: Exploded view of locomotion segment

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.

IV.II. 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.

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.

V. FABRICATION AND TESTING

After completing the preliminary and critical design phase, the UAH design team proceeded to manufacture a prototype of the locomotion segment of the LW. Tools for fabrication were provided by the machine shop located on the UAH campus. The tools included a CNC milling machine, lathes, drill presses, vacuum pumps and vacuum bags for composite lay-ups, shears, and assembly tools such as screw drivers and wrenches. From receiving parts to final assembly, the fabrication phase was performed in approximately three weeks. Figure XV is a skeletal view of a four segment system excluding the wiring conduit and the electronic control boards. The addition of composite side walls to the assembly can be seen in Figure XVI.

Fig. XV: Skeletal structure of the LW prototype

Fig. XVI: LW prototype without protective skin

V.I. Problems and Solutions

Within days of the Product Readiness Review (PRR) held at NASA's MSFC, the team encountered various obstacles in the final assembly and testing. The most concerning problem was the implementation of the Power Control Board (PCB) and the master slave configuration. The team was unable to produce a solution in the time necessary before the PRR. However, the team decided on an alternative method of providing power and control to the LW in order to demonstrate the product's viability. Two demonstration units were prepared for the PRR- one unit demonstrated multiple segment actuation and one unit demonstrated the force necessary to compress the composite sidewalls (see Figure XVII below).

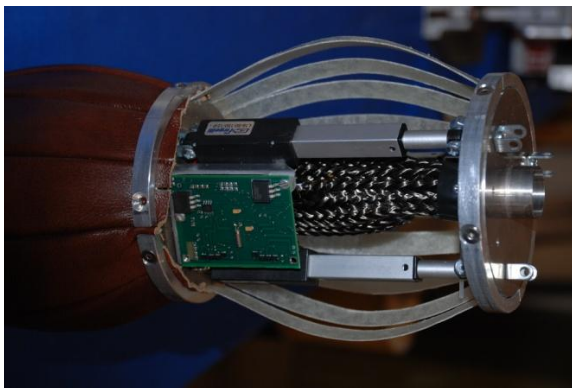


Fig. XVII: Demonstration segments revealing inner and outer components

V.II. Verification Testing

In order to satisfy the requirements given by the technical advisors, a series of verification tests were to be performed by the UAH design team. These various tests were to be performed on a component level, sub-assembly level, and assembly level.

V.II.I. 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 III). These results showed that the system was not as efficient as originally projected, which therefore raises the power requirement of system.

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

Table III: Side wall force and efficiency test

V.II.II. Electronics Functionality Test

This test was designed to be a systems check for the electronics to make sure they work before installation. The required equipment was to be comprised of a volt meter and a power source. Since a demonstration unit was necessary for PRR, an Arduino Mega controller was programmed and used in place of the PCB master slave configuration. This allowed the L-16 actuators to sequentially extend and contract. The Arduino Mega controller, however, was not able to withstand the amount of power necessary to properly deflect the composite side walls to allow peristaltic motion. Proper configuration of the PCB and master slave system would have allowed the peristaltic motion to occur and will be utilized in future prototype designs. Each slave board can withstand 8 A at 12 V through its two L298 IC's, giving this high power driver board a power rating of 96 Watts. Yet it also contains the speed of eight parallel processors running at 80 MHz. This original designed PCB actually allows the ENTIRE LW system to be controlled with only three wires in tether system, instead of six per SEGMENT, which would overwhelm the central *blue* conduit. By having three actuators per segment, a 96 Watt rating, and excess processing power, additional testing of the intra- and inter- segment communication protocol will allow for full three dimensional movement, all controlled by three slave boards should the others six fail. A key mission reliability element.

V.II.III. Force Output Test

The original test proposed involved the use of load cells mounted between the actuators and the bulkhead to measure the output force of the actuators. Additionally, a grouping of load cells was to be placed radially about one segment to measure the total force generated by the side wall members. It was also desired to test the strain placed upon the sidewall members at various points along their length via affixed strain gages. The level of strain endured by the side wall members is important because it allows for determination of lifespan and potential future material choices.

Due to several delays in the procurement and manufacturing phases, it was not possible to implement the desired two week testing regime described above. Ultimately, only the output force from the sidewalls was verified. Furthermore, only the minimum magnitude was obtained, which unfortunately does not give any direct correlation to the actual force produced except that it is over the minimum threshold.

The items used in this test were a completely integrated LW segment (excluding control electronics), a laboratory power supply with voltage and current control, a six inch inside diameter plastic pipe, and a simple kitchen scale.

Using the power supply with 12 volts output, the power to the actuators was gradually increased until they began moving. Movement generally occurred around 0.2 Amps (or approximately 6 Watts). The actuators were then allowed to compress the sidewall strips until they pressed the skin into full contact with the interior of the pipe and caused the actuators to stall. The bulkhead of the segment was gripped and the pipe was lifted free off the ground so that the entire weight was supported by the frictional force of the segment on the pipe wall. The pipe was then weighed and found to be 8.6 lbf. Using the data gathered, the minimum sidewall force exerted was determined using an assumed maximum frictional coefficient of 0.5. Thus the sidewall force must have been in excess of 17.2 lbf (76.5 N). Also, the power required to achieve this loading level is around 6 Watts.

VI. FUTURE WORK

High temperature components: Using piezoelectric linear actuators like the PiezoMotor® Piezo Legs® LTC45011 (which can produce 450 N and withstand 250°C+ temperatures) a pending NASA Planetary Instrument Definition &. Development Program (PIDDP) proposal aims to create a light weight mechanically simple support structure to resourcefully orchestrate, the actuation of the segment subsystem in its extreme environment. The proposed structure will parallel the temperature performance characteristics of the piezoelectric actuators by transferring thermal loads to a pneumatic radiator system or the regolith directly, thus protecting all the LW's electrical components and providing the structural precision (low thermal expansion coefficient) needed for the space constrained environment. System integration work on high temperature control electronics is also very important. Suggestions include the use of ceramics as a PCB base material, Silicon-on-insulator (SOI) technology to isolate devices on the IC dielectrically, instead of relying on reverse biased junctions in a standard Si process, and the use of silicon carbides intrinsic material properties [10]. Thus allowing electronics to handle 250°C+ temperatures.

Outer contamination layer: Similar to space suit technologies, developing a multiple layered covering is essential for proper robotic platform performance / minimizing regolith contamination. This dust shroud needs to be self-lubricating, impermeable, and durable. The pending PIDDP thus incorporates design ideas such as the use of Teflon and a thermally bonded orthro-fabric and urethane single layer, from a commercial space suit company - Final Frontier Design ©. Who is a subcontractor of the proposal.

Injection of compressed inert gas: It has been demonstrated in previous research by Dr Khalid Alshibli, that injecting compressed gas can help loosen and break up the regolith particles to facilitate drilling. This gas could also be used to keep the drill clean of debris and cool the internal electronics. A method for incorporating such a system into the proposed platform should be investigated. This multiuse system ensures overall simplicity and electronic longevity, which decreases by a factor of two for every 10 degrees above rated temperature [11].

Regolith transport simulation software: The construction of a high fidelity combined Discrete Element Method (DEM), Multi-Body Simulation (MBS), and Soil Contact Model (SCM) [12] ***subterranean*** simulation using SimPack® or the NASA SBIR funded *Enhanced Mesh-free Simulation of Regolith Flow* software would be of great benefit. It would substantiate that the peristaltic motion of our robotic segments can transport the unique regolith (very compact, jagged & interlocking, and small (50 µm)) along and behind the LW. This upgrade to the German Aerospace Center (DLR) or Grainflow Dynamics, Inc. software would also further the field of rover locomotion, via better excavation, slope stability, and wheel traction analysis. All of which are essential for better robotic regolith mobility development [13].

VII. CONCLUSION

For the UAH student design team, the goal was to design and build a prototype that could possibly one day take soil samples on the moon. In attempting to achieve this goal, the team learned many valuable lessons. Each member was given an opportunity to apply and appreciate the engineering fundamentals learned in the classroom. Team dynamics and project organization via NASA systems engineering engine were essential in successful progress of the mission. With so many lessons being learned through the course of the project, the UAH team was able to successfully manufacture two demonstration prototypes that showed the viability of the Lunar Wormbot project. The projects success has led to the writing of a $400k NASA NSPIRES proposal, which is still pending and the continuation of system refinements and additions as another UAH senior design team project during the 2011 – 2012 school year. The licensing of several subsystems is also under discussion with the JURBAN Google Lunar X-Prize team, for actual use on the Moon in the latter part 2014.

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