In fulfillment for the University of Alabama in Huntsville Honors Program
SEgmented Robotic Platform for Exploration, seNsor Transport and Sampling (SERPENTS)
MAE 490-02 / 491-02 Introduction to Product Realization Team 2

Honors Student:

Mallory Brown, mkb1081@uah.edu
229-S NCRH, 1303 Ben Graves Drive, Huntsville, AL 35816

Faculty Advisor:

Dr. Christina Carmen, Senior Design Class Instructor, Christina.Carmen@uah.edu
UAHuntsville, Mechanical and Aerospace Engineering Department
Technology Hall N224, Huntsville, AL 35899

Customer/Advisor:

Blaze Sanders, NSSTC, blaze.sanders@solarsystemexpress.com
Phone: (607) 591-1206

Sponsors/Special Acknowledgements:

Alabama Space Grant Consortium (ASGC)
UAH Office of the Vice President of Research (OVPR)
UAH Dean of College Of Engineering (Dean of COE)
UAH Mechanical and Aerospace Engineering Department (MAE)
The National Space Science and Technology Center (NSSTC)
The Reliability and Failure Analysis Laboratory (RFAL)

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1. Introduction (Mallory Brown)

Collection of lunar regolith was a critical aspect of the National Aeronautics and Space Administration (NASA) Apollo space program. From 1969 to 1972, NASA collected samples of lunar regolith on six different missions; thus enabling geologists to determine the mineral composition of the moon and how the lunar surface was impacted by extraterrestrial events (Lunar and Planatary Insitute). However, the maximum depth retrieval that the Apollo astronauts achieved was limited to three meters due to the logistical difficulty of the task. In order to broaden the understanding of lunar and other planetary regolith, future space missions will require a tool capable of coring to unexplored depths via an automatic device capable of collecting soil samples from varying depths.

The SEgmented Robotic Platform for Exploration, seNsor Transport and Sampling (SERPENTS) project was initiated in order to design a robotic device intended to collect regolith samples from deeper depths than had been previously achieved. The project originated with a NASA Robotics Academy design team at Marshall Space Flight Center (MSFC) in 2010. The team worked with the National Space Science and Technology Center (NSSTC) on the SERPENTS conceptual design before the project was transferred to the University of Alabama in Huntsville (UAH) and Louisiana Tech (LA Tech) in August 2010 for further design refinement, fabrication, and testing.

The UAH design team was charged with the task of replicating the peristaltic motion of an earthworm to propel the body of the SERPENTS robot through various regolith depths. The design, fabrication, and testing of the SERPENTS robot by the UAH team was completed utilizing NASA Systems Engineering (SE) design processes (Figure 1). The 2011 fall semester completed work on the system design phase, and the 2012 spring semester completed the product realization phase and worked towards the technical management phase. The UAH SERPENTS design team completed extensive technical analysis associated with the structural load conditions, material stresses, and deflections. The UAH team also completed extensive verification tests including cyclic and bending compression tests in conjunction with the UAH Reliability and Failure Analysis Laboratory.

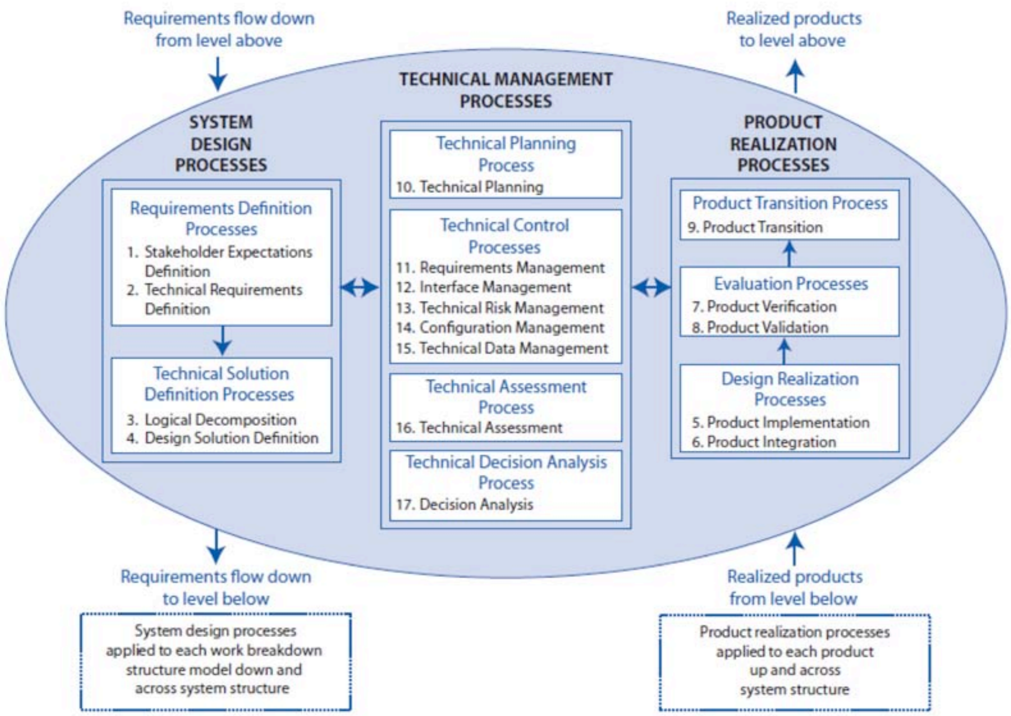

Figure 1: NASA's System Engineering Design Engine

Photo Provided by Dr. C. Carmen

The ultimate goal for the system is to become an instrumental platform, specifically in the scientific exploration of Mars and the moon, though applicable to other planetary bodies- including the Earth. The ability to return scientific samples at various depths, make in-situ measurements, or act as a sensor deployment system will open the door to previously unexplored scientific regions. The present paper will provide an overview of the SERPENTS project, with an emphasis on the UAH design, fabrication, and testing of the SERPENTS body segments.

The 2011-2012 SERPENTS Team consisted of the following members:

Mallory Brown, Team Lead, mkb1081@uah.edu
229-S NCRH, 1303 Ben Graves Drive, Huntsville, AL 35816

Michael Pinkston, mcp0003@uah.edu
166 Kelly Spring Road, Harvest, AL 35749

Johnny Dingler, johnny.w.dingler@ulalaunch.com
169 County Road 1493, Cullman, Al 35058

Nathan Wiseheart, naw0004@uah.edu
16822 Woodhaven Drive, Athens, AL 35613

Randy Brackins, rdb0004@uah.edu
6675 County Road 203, Danville, AL. 35619

2. Purpose (Mallory Brown)

The purpose of the 2011-2012 SERPENTS Team is to continue to design, fabrication, testing, and assembly of a robotic burrowing device for use on the lunar regolith. The SERPENTS shall be capable of burrowing to a fixed depth, collect 50 one-gram samples, and return with them to the surface. The SERPENTS's burrowing shall be achieved through the use of an ultrasonic drill bit and a conical auger, and by the peristaltic motion of the body segments. The UAH SERPENTS Team is responsible for the body segments, while the head section, soil collection segments, and support structure are the responsibility of various other teams. The Head section is specifically under the design and fabrication of the Louisiana Tech University (LA Tech) SERPENTS Team.

2.1 Mission Statement (Mallory Brown)

The Mission Statement for the SERPENTS project is as follows: The project goal is to develop knowledge in order to enable a robot to operate on the lunar regolith in order to obtain soil samples from varying depths. The SERPENTS should be capable of burrowing through fine particulate soil simulant to a fixed depth, and return to the surface with collected data and samples. A prototype of the robot, to be produced during the project timeline, is to be designed for Earth-based testing. The goal of the UAH Team is to design and fabricate the body segments that should be capable of moving using peristaltic motion. (Brown and Pinkston 6)

2.2 Honors Project

The abstract found in Appendix A, was submitted to the 63rd International Astronautical Congress (IAC). The conference will take place in Naples, Italy from October 1, 2012 – October 5, 2012. The IAC is a professional conference hosted by the International Astronautical Federation (IAF) with the International Academy of Astronautics and the International Institute of Space Law (IISL), which is attended by many of the leading minds in the aerospace, aviation, and aeronautics communities (International Astronautical Federation). The conference accepts abstracts from all disciplines, and UAHuntsville sends students from all majors annually. This work was completed to contract the MAE 490/491 project with the UAHuntsville Honors Program. The abstract written for the work completed on this project was selected for the A.3 Space Explorations Symposium as a poster. The poster shall be completed in the upcoming summer semester.

3. Activity Plan / Schedule (Mallory Brown)

The work done on the SERPENTS project by the University of Alabama in Huntsville (UAH) SERPENTS team was split between the fall 2011 and spring 2012 semesters. The fall 2011 work was split between the team members on the team at the time, Mallory Brown and Michael Pinkston. The spring 2012 work was split between all five members of the extended SERPENTS team. The fabrication of the fiberglass was handled by Randy Brackins and Johnny Dingler, and the programming and wiring of the SERPENTS was handled by Nathan Wiseheart. All work completed by the team during the fall 2011 semester can be found in the Gantt Charts in Figures 2 and 3. All work completed on the project during the spring 2012 semester can be found in Figure 4.

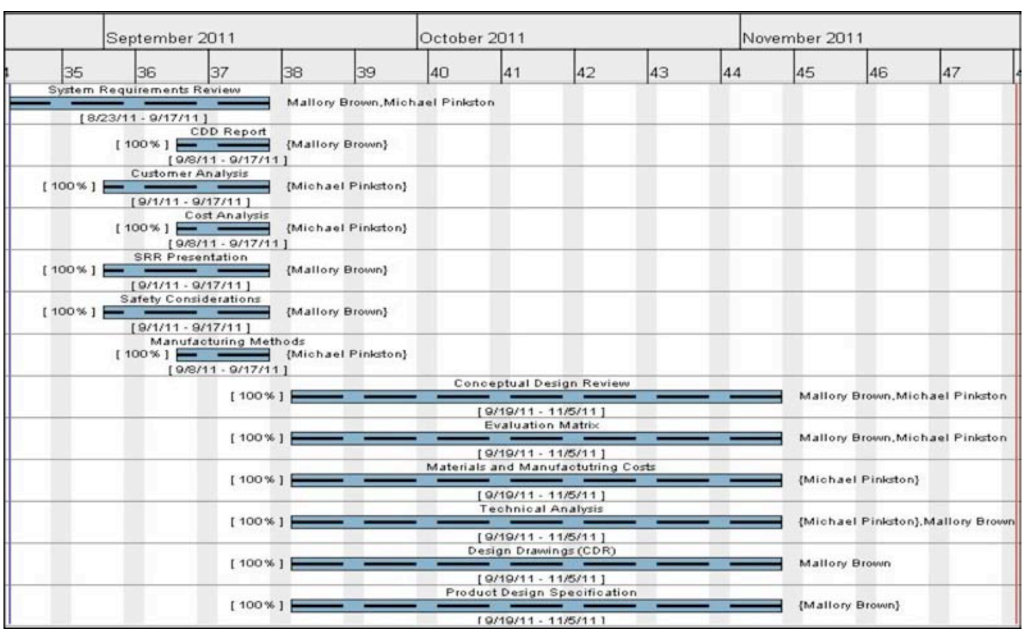

Figure 2: Team 3 Activity Plan August – November 2011 Timeline

Photo Provided by M. Brown

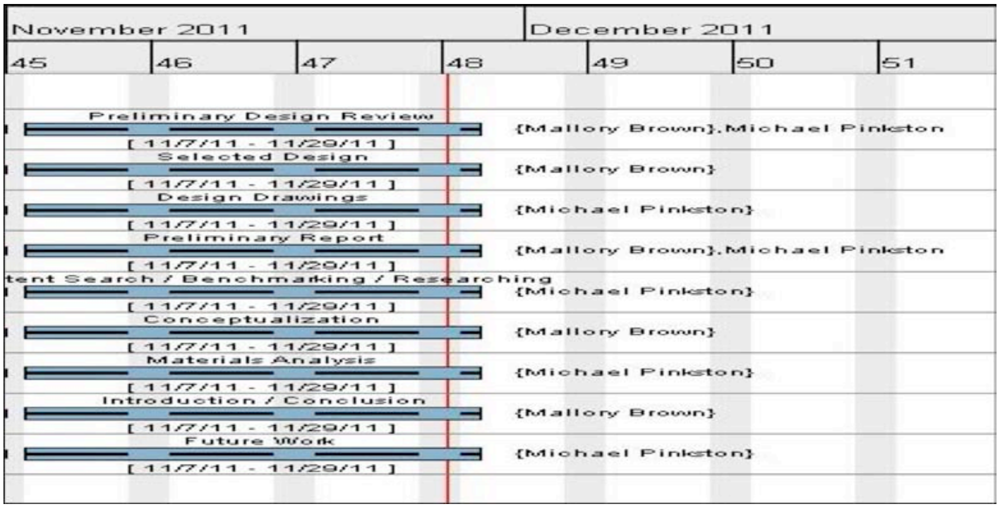

Figure 3: Activity Plan November 2011- December 2011 Timeline

Photo Provided by M. Brown

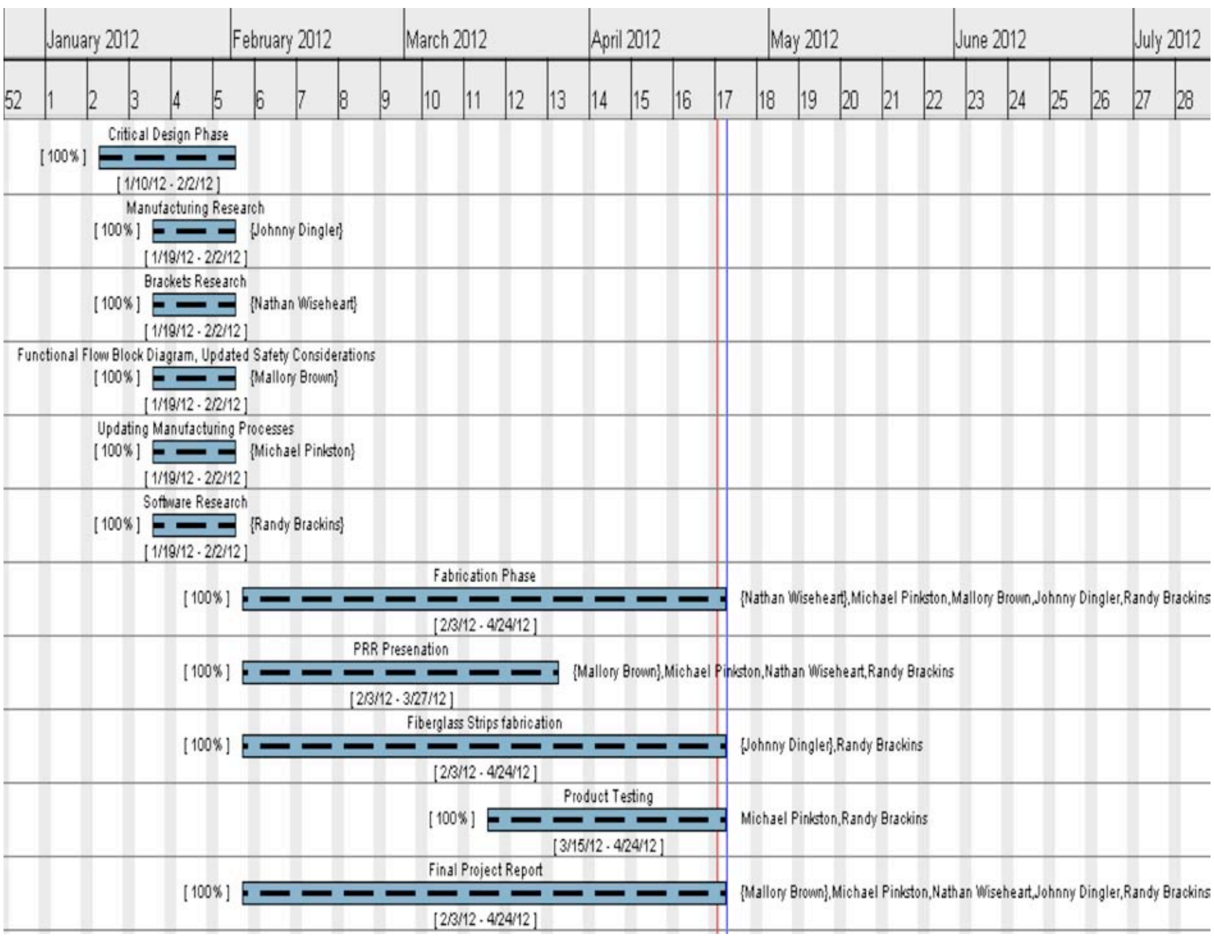

Figure 4: Activity Plan January 2012 - April 2012 Timeline

Photo Provided by M. Brown

4. Main Design Reviews (Mallory Brown, Michael Pinkston, Johnny Dingler, Nathan Wiseheart, Randy Brackins)

4.1 System Requirements Review (SRR)

The first design review conducted for the 2011-2012 SERPENTS Team was the System Requirements Review. This design meeting was held in order to establish the mission requirements, review the Concept Design Document (CDD), establish preliminary cost estimation, a review of current designs pasted onto the design team, and an overview of the manufacturing methods that may be employed.

4.2 Conceptual Design Review (ConDR)

The second design review of the SERPENTS project was the Conceptual Design Review. This review was conducted to discuss and review the conceptual designs for the fiberglass stripes design, establish the preliminary safety requirements of the project, a review of the Product Design Specification (PDS), provide the evaluation matrix, and provide the technical analysis done on the design concepts. The cost analysis started at the last review was also updated, along with some of the proposed manufacturing techniques and materials to be used.

4.3 Preliminary Design Review (PDR)

The last design review completed during the fall 2011 semester was the Preliminary Design Review. The PDR was conducted in order to update the customer about the concept designs, update the safety, manufacturing and cost information, and provide the completed CAD modeling of the proposed design. The main goal of the PDR was to get the project ready for the fabrication in the upcoming 2012 spring semester.

4.4 Critical Design Review (CDR)

The first design review of the 2012 spring semester was the Critical Design Review. The CDR was conducted to update the customer on any changes to the project made between the semesters and during the beginning of the new semester. The review also looked at the renewed technical analysis, the updated safety considerations (that included the manufacturing and testing hazards that were not previously included), a review of the verification tests to be accomplished once fabrication was complete, and an update to the CDD to include the new bracket and programming requirements.

4.5 Product Readiness Review (PRR)

The final design review conducted by the 2011-2012 SERPENTS Team was the Product Readiness Review. The PRR was conducted to inform the customer about the manufacturing methods and materials using during the fabrication of the hardware, reviewed the created Fault Tree Analysis and Concept of Operations, reviewed the verifications tests performed, and reviewed the Verification Table for the hardware. The finished hardware was not delivered to Dr. Carmen at this time.

5. Conceptual Design (Mallory Brown, Michael Pinkston, Nathan Wiseheart)

The 2011-2012 SERPENTS Team began the conceptual design phase of the project immediately after starting the project. The team began this phase by establishing the system requirements to be used over the project timeline. The team also analyzed the existing hardware and the researched other potential design solutions. The team designed several different concepts for the fiberglass strips that were on the original hardware and evaluated how well each design (the original strip design or the proposed concepts) would meet the system requirements. This was accomplished using an evaluation matrix and some technical analysis. During this phase in the project, the team also came up with a preliminary budget and cost analysis, and analyzed the safety concerns presented by the SERPENTS.

5.1 Project Requirements / Concept Design Document (Mallory Brown)

During the 2011 fall semester, the SERPENTS team completed a Concept Description Document (CDD) to define the major parts and requirements to be addressed during the project timeline. The CDD was conducted to establish the requirements and layout of the project work to be accomplished during the project timeline. The requirements agreed upon for the project are below. The team name in parenthesis after the requirement refers to the team responsible for the requirement. A revised CDD was created during the 2012 spring semester as circumstances changed some of the scope of the project. The requirements were expanded to include the brackets attached to the bulkheads and the programming of the peristaltic motion through the Arduino board. A full copy of the CDD can be found in Appendix B. The revision number of the CDD shown in Appendix B is Revision 02.

- Requirement 1. The SERPENT shall be capable of burrowing through fine particulate matter. (UAH Team)
- Requirement 2. The SERPENT shall implement peristaltic locomotion to allow one-dimensional burrowing. It should have segments articulated in three dimensions. (UAH Team)
- Requirement 3. The SERPENT shall be designed for Earth-based testing. (UAH Team, LA Tech Team)
- Requirement 4. The SERPENT shall take 50 one-gram samples at a specific interval over the 15m burrowing depth (LA Tech Team).
- Requirement 5. The SERPENT shall utilize a power supply of 5 W or less (UAH Team).
- Requirement 6. The SERPENT's head section shall be made up of an ultrasonic drill bit and a conical auger (LA Tech Team).
- Requirement 7. The SERPENT shall utilize an elastic water-tight skin to protect the interior electrical and mechanical systems from the fine particulate matter (UAH Team).
- Requirement 8. The SERPENT shall incorporate the space to include a navigational and sensory package (UAH Team, LA Tech Team).
- Requirement 9. The SERPENT shall be capable of returning to the surface to deliver the soil samples (UAH Team).
- Requirement 10. The SEPRENT shall be capable to survive multiple missions of burrowing 15 m then ascending back to the surface (UAH Team).
- Requirement 11. The SERPENT should apply mechanical force by means of motors or actuators situated perpendicular to its longitudinal axis (UAH Team).
- Requirement 12. The SERPENT shall be analyzed using modeling and simulation techniques prior to prototype testing. (UAH Team)
- Requirement 13. The SERPENT auger shall be designed to optimize soil displacement and forward motion (LA Tech Team).
- Requirement 14. Individual dummy segments shall be between 50% and 90% of locomotion segment volume (LA Tech Team).
- Requirement 15. The SERPENT shall produce at least 66 N of force directed perpendicular to the segment's longitudinal axis at the center hinge (UAH Team).
- Requirement 16. The SERPENT shall be designed to withstand temperature extremes on the lunar surface (UAH Team, LA Tech Team).
- Requirement 17. The SERPENT shall be provided with electrical power through the use of a

cable extended from the surface (UAH Team).

- Requirement 18. The SERPENT shall be tested at the KSC test bed in May 2012 (UAH Team).
- 2.3.19. Requirement 19. The brackets attaching the linear actuators to the bulkhead will allow for 3 dimensional movements (UAH Team).

5.2. Patent Search (Michael Pinkston)

The following patent search was conducted during the fall 2011 semester by the SERPENTS Team. A patent search provides an opportunity to review similar products which may contain desirable characteristics which can be incorporated into the project design. It also is necessary to ensure that no patent on a similar product is violated in any way. Over 50 patents were reviewed, ranging from peristaltic motion to ultrasonic drills. Of the patents viewed, none provided any improvements over the design chosen by the previous team. A patent for the SERPENTS is currently in the process of being completed by Blaze Sanders and the previous SERPENTS team (Brown and Pinkston 10).

5.3 Benchmarking / Market Survey (Michael Pinkston)

The following benchmarking and market survey were conducted during the fall 2011 semester by the SERPENTS Team. The products that were the main focus of research were ultrasonic drills. The products viewed provided insight into how ultrasonic drills function, but none the drills researched provided any benefit or displayed any characteristics that are more desirable than the current ultrasonic drill design.

A wormbot design from Chuo University displayed design elements that are desirable to the SERPENTS Project. Chuo University's wormbot contains thin-walled sections which are capable of easily bending, enabling the wormbot to expand and contract easily. This device does not contain a drill bit, as it is designed to travel through existing pipes, and is not designed to drill through solid material.

As the SERPENTS team is continuing the project from a previous team, no market survey was conducted, though the previous team was contacted regarding design decisions and for information gathering. (Brown and Pinkston 11)

5.4 Research / Information Gathering (Michael Pinkston)

Research into companies that the composite strip construction could be outsourced to was done. It was found that very few companies exist that work in fiberglass composite construction, and it was decided that the composite strip construction would be done by the team, under the supervision and with the instruction of Dr. Wessels and the Reliability Lab.

During the Fall 2011 Semester, the team spoke with the previous SERPENTS team, as well as with customer representative Blaze Sanders, and discussed with them what changes, if any, should be made to the SERPENTS. With the input from these two sources, the team was able to focus their efforts towards the critical sections needing work. (Brown and Pinkston 11)

5.5 Conceptualization and Trade Studies (Mallory Brown, Michael Pinkston, Nathan Wiseheart)

During the fall 2011 semester the team focused on two aspects of the previous Lunar Wormbot to redesign. The two main sections of the Wormbot that the SERPENTS Team redesigned was the fiberglass strips that surrounded the body segments and transferred the force from the actuators unto the tunnel walls when the SERPENTS is in motion, and the skin that protects the internal components from damage. During the spring 2012 semester, conceptualization was done on a third portion, the brackets that hold the actuators to the bulkheads.

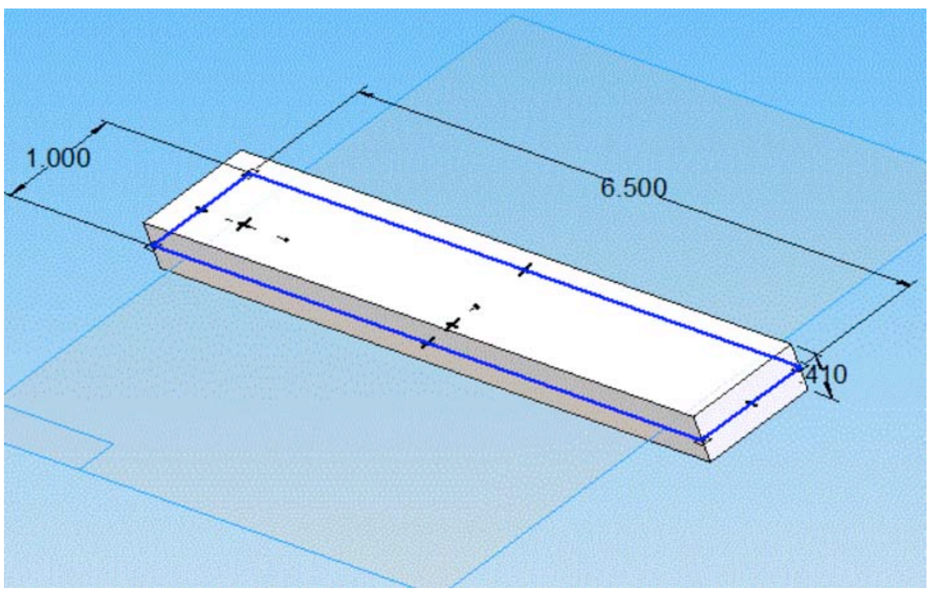

Figure 5: Concept Design 1 (all dimensions are in inches)
CAD Drawing provided by M. Brown

For the fiberglass strips, two new conceptual designs were evaluated against the previous design. As seen in Figure 5, the first concept design (Concept Design 1) was the previous design.

This design was made of up of multiple thin fiberglass strips (unattached to one another) was connected to the bulkheads to translate the actuators' longitudinal force. As seen in Figure 6, a second design concept (Design Concept 2) was one of the two new designs. This design was made up of one single flat plate of fiberglass in which multiple width-less slits was cut into the fiberglass. The flat sheet was then rolled around the body segment. And lastly, as seen in Figure 7, a third design concept (Design Concept 3) was the second new design. This design was also made up of a flat plate of fiberglass where ½ inch wide windows were cut out of the material. The sheet was also wrapped around the body segment.

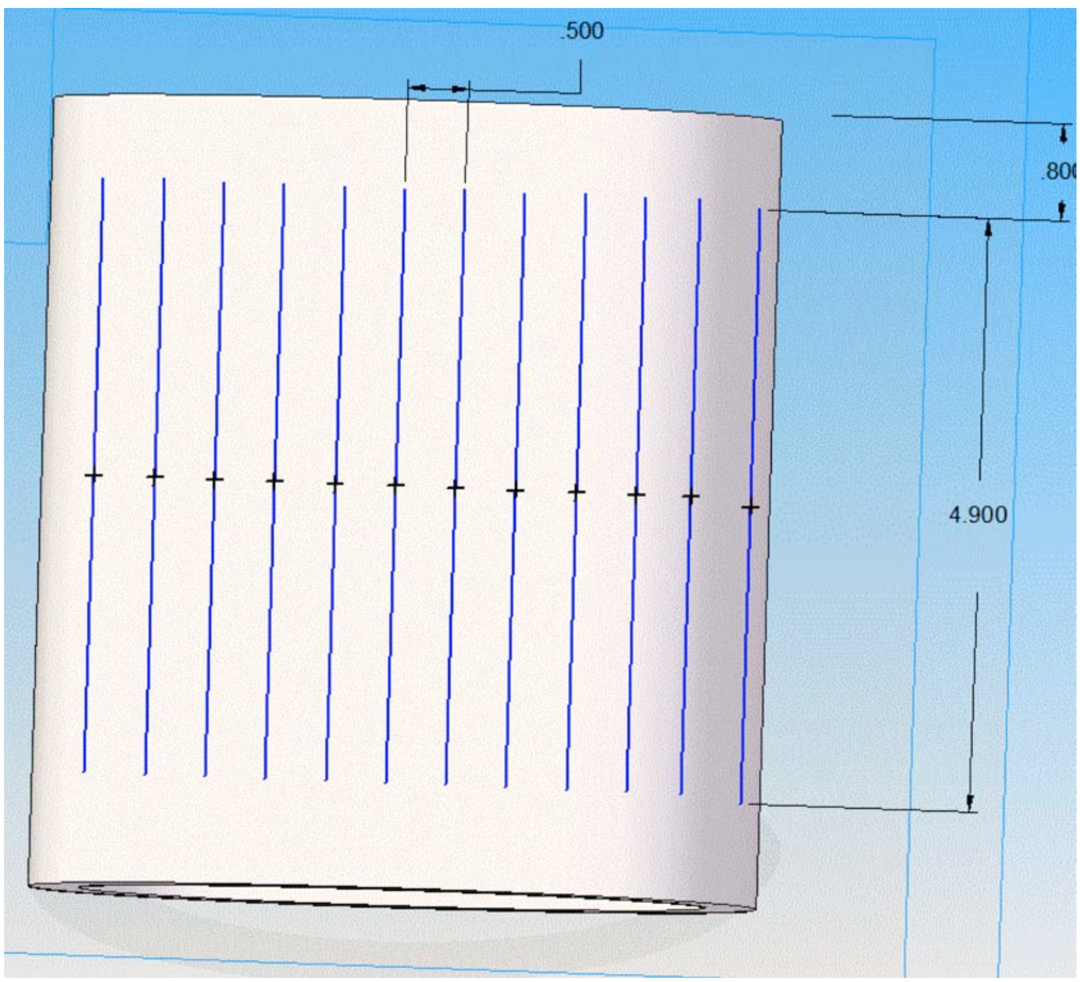

Figure 6: Concept Design 2 (All dimensions are in inches.)
CAD Drawing provided by M. Brown

The other main aspect of the Wormbot that was assessed for redesign was the external skin. The first design considered was the inherited leather skin used previously. The new design was of a pressure suit material that Mr. Blaze Sanders proposed that the team look into.

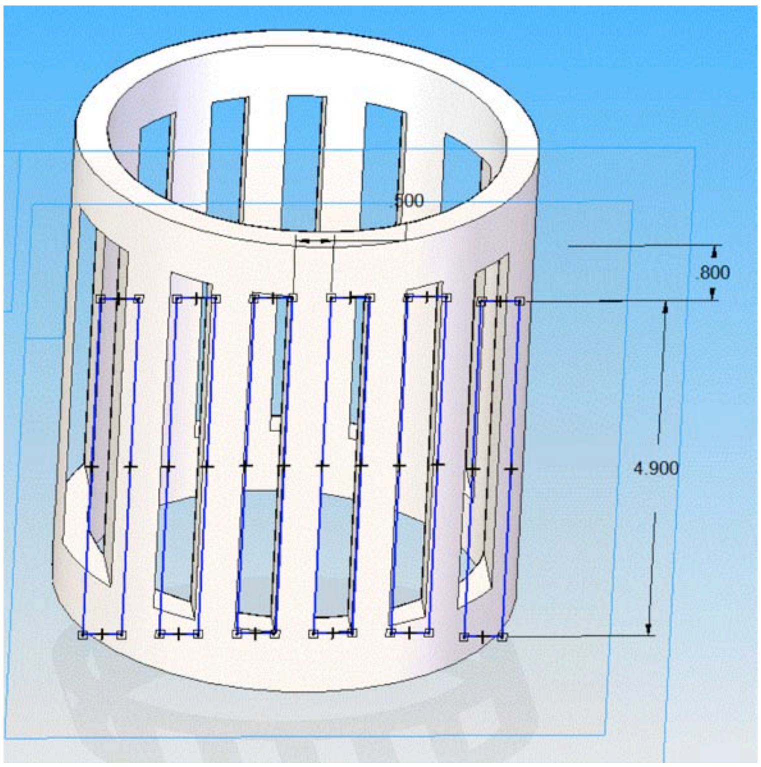

Figure 7: Concept Design 3 (All dimensions are in inches.)
CAD Drawing provided by M. Brown

Each concept was evaluated using an Evaluation Matrix (Table 1 for the fiberglass strips, and Table 2 for the skin). It was determined that the width-less strip design, and the pressure suit material provided a better improvement over the original designs. The width-less strip design provides easier maintenance and installation, while still maintaining the needed strength on the whole walls, and the space suit material provides a stronger, more resistant skin than the leather material (Brown and Pinkston 12-13). For fabrication, however, it was decided to fabricate both Concept Designs 2 and 3 and decide which would go on the final hardware though material and

Table 1: Strip Evaluation Matrix

				Previous Design - multiple fiberglass stripes	1 sheet of fiber glass with width-less slits	1 sheet of fiberglass with 1/2in slits
Criteria	Mandatory (Y=1, N=0)?	Weight	Scale			
Mission Success	1	15%	3 -best 1-worst	1	2	2
Crew Operational Safety	1	20%		2	2	2
Recoverability of SERPENT	1	15%		1	2	3
Successful Soil Collection	1	20%		1	3	2
Production Cost	0	5%		1	2	2
Durability of Stripes	0	10%		1	3	2
Ease of Production	0	5%		1	3	2
Effectiveness of Bulkhead connection	1	10%		2	3	3
Weighted Total		100%		43%	82%	75%

Table 2: Outer Skin Evaluation Matrix

				Previous Design - Leather skin	donated Space-rated skin
Criteria	Mandatory (Y=1, N=0)?	Weight	Scale		
Mission Success	1	30%	2 - best 1 - worst	2	2
Protection of Internal Components	1	30%		2	2
Cost	0	5%		2	1
Durability of Material	0	20%		1	2
Elasticity	1	15%		1	2
Weighted Total		100%		83%	98%

product testing.

During the spring 2012 semester, the brackets were evaluated for redesign because Mr. Blaze Sanders had reported trouble with the actuators twisting and potentially breaking due to the brackets only allowing for one-dimensional movement. However, during the first actuator tests while the bracket design was conceptualized, it was discovered that if set to certain parameters, the actuators wouldn't contort, therefore no further conceptualization was completed with the brackets. The original design was then unanimously decided to be kept. The concept

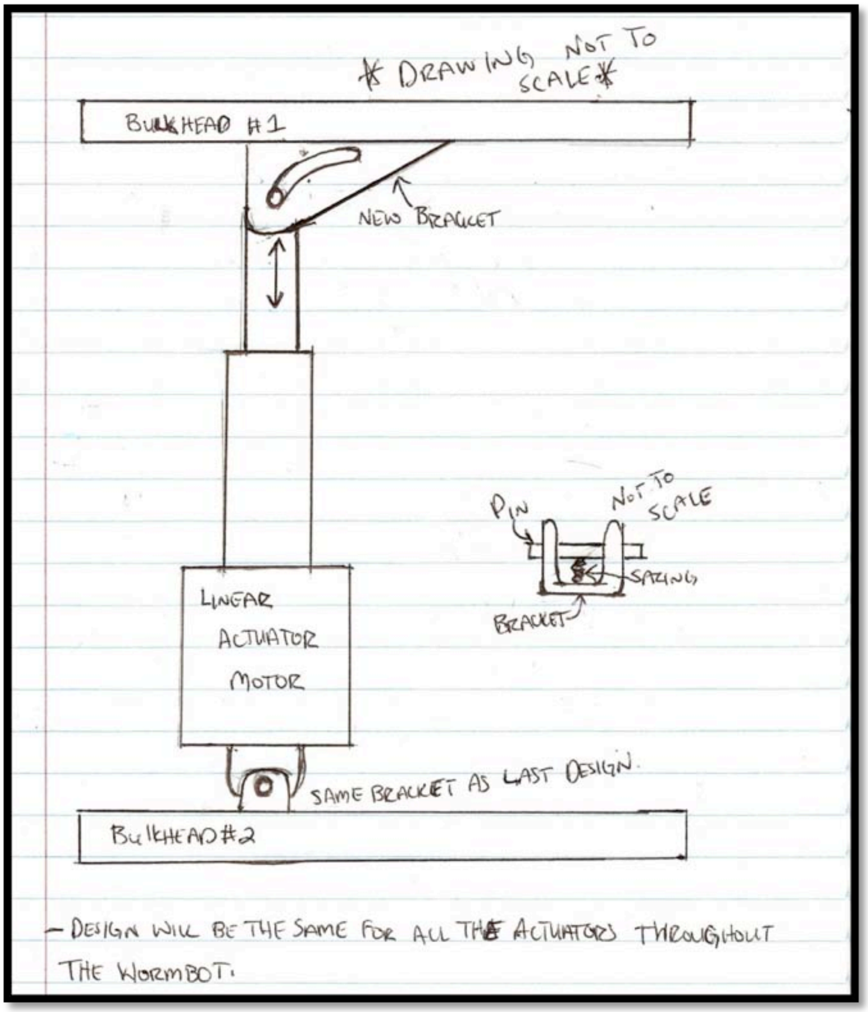

Figure 8: New Bracket Design

Drawing provided by N. Wiseheart

6. Preliminary Design (Mallory Brown, Michael Pinkston)

The second phase of the project for the 2011-2012 SERPENTS Team was the preliminary design phase. After evaluating and assessing the potential design concepts, the team concluded that the width less design was the design that would be fabricated during the fabrication phase of the project. The team also decided to fabricate the second choice concept (the ½ inch window design) to compare with the top design and the fiberglass strips fabricated by the 2010-2011 Wormbot team. The team refined the technical analysis done on the design and updated the cost and safety considerations. The preliminary phase was the time for the fall 2011

SERPENTS team to get ready for fabrication during the 2012 spring semester.

6.1 Concept of Operations (Mallory Brown)

The Concept of Operations (ConOps) developed for the SERPENTS project during the spring 2012 semester was created for the overall combined project once completed. The ConOps includes the functions and sequence of events needed to complete a sample retrieval mission from the lunar surface. As shown in Figure 9, the mission's schedule has necessary events to occur in order to complete the specified mission.

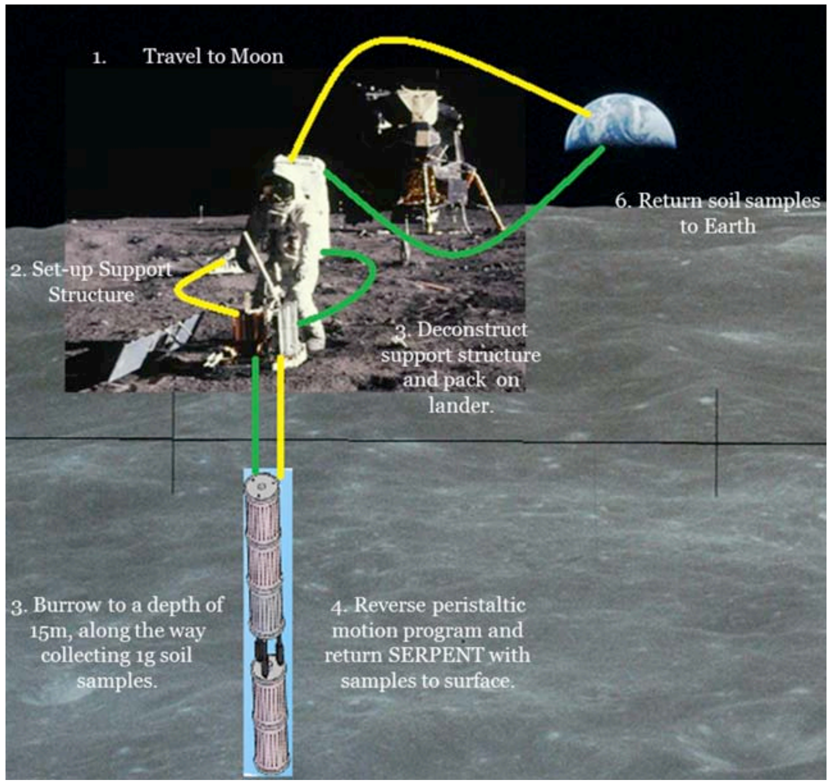

Figure 9: SERPENTS ConOps

Photo Provided by M. Brown

The 1st step of the mission operations is for a human crewed mission to travel to the moon. The SERPENTS is not autonomous, and thus needs a crew of trained personnel in order to accomplish the mission. The 2nd step is to ready the survey sight for the SERPENTS burrowing, unpack the SERPENTS from its travel assembly, and to set up the support structure apparatus. The 3rd step is for the SERPENTS to be powered up and deployed to the required depth (15 m), collecting one gram samples along the way. The 4th step is for the SERPENTS to stop the peristaltic forward motion program and begin the reverse motion program in order to extract the SERPENTS from the lunar regolith. The 5th step is to disassemble the support structure and pack up the SERPENTS for the return trip to Earth. The final step of the mission operations is to return the crew, SERPENTS, and samples to Earth.

6.2 Design Concept (Mallory Brown, Nathan Wiseheart)

The fiberglass strips design that was chosen was the width-less strips concept as seen in section *5.5 Conceptualization*. As shown in Figure 10, the design is composed of a single sheet of fiberglass that is wrapped around the body segment. Slits were cut into the fiberglass at constant intervals in order to allow the sheet to bend and bow outward without breaking (as shown in Figure 11). This design was chosen over the previous design (individual strips) and the other design concept (1/2 inch windows) for a number of reasons. The first reason that the design was chosen over the alternatives was that with a full sheet surrounding the entire segment instead of multiple individual strips, the fiberglass would be held to the bulkheads by the retainer rings. One problem seen with the previous design of the fiberglass was that the strips fell out of the assembly very easily if the actuators extended outside the set acceptable parameters. In order to achieve the applied load needed by the design, a pinned-pinned column situation was required. Thus, the retainer rings could not grip the fiberglass firmly or the rings would change the stress points in the fiberglass. By going with a full sheet of material, the fiberglass sits more stable in the groove of the retainer ring and the bulkhead.

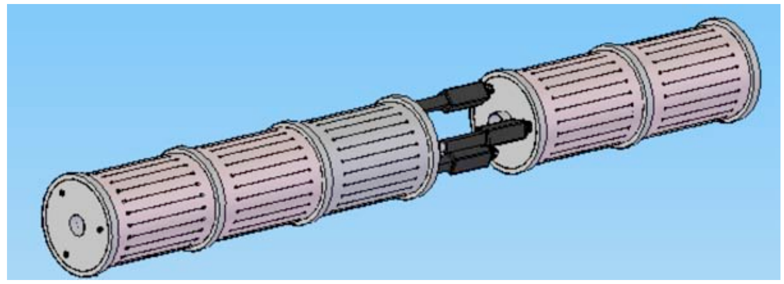

Figure 10: Selected Design
CAD Drawing provided by N. Wiseheart

The second reason the design was chosen over the alternatives was that the width-less slit design was chosen over the alternatives was that the combined plate of fiberglass was transfer the load of the actuators better than the individual strips. As seen by the verification tests (see section *7.6 Verification Tests* for further details), the thicker strips could support a heavier load than the thinner strips. The team reasoned that by

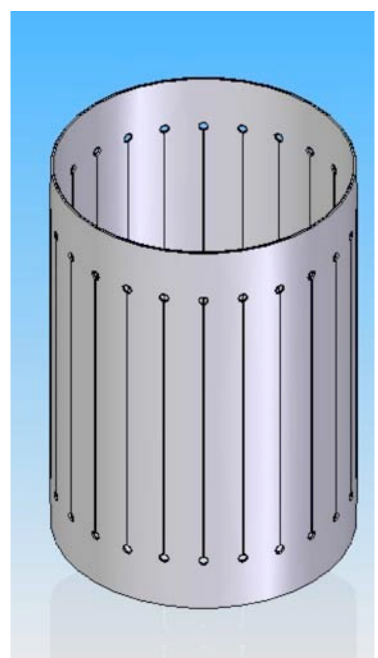

Figure 11: Selected Design
CAD Drawing provided by N.

distributing the load across multiple strips tied together, they would be able to support a larger load than if each individual strip had to carry the full load.

A third reason that this design concept was chosen to move forward into fabrication was the thought that the fiberglass would be able to hold a greater load than the single individual strips but not be too difficult for the actuators to compress. One of the difficulties discussed about the ½ inch windows design was because there were gaps where not fiberglass would be transferring the load; a greater load would be bearing down each strip. This would cause each strip to push back with as great a force due to Newton's 3rd Law. It was discussed that this design might be too strong for the actuators to contract. The selected design, on the other hand, would avoid this problem due to having a consistent layer of fiberglass around the entire diameter of the body segment.

The last reason that the width-less slit design was chosen over the ½ inch windows design was ease of manufacture. Cutting slits into a flat plate of fiberglass was determined to be much easier that trying to lay little ½ inch wide gaps in the fiberglass. Having a full plate of fiberglass would also be easier and less time consuming to manufacture than many multiple smaller individual strips due to having to cut the strips out of the plate after layup.

6.3 Material Analysis (Michael Pinkston)

The following material analysis was done during the fall 2011 semester by the SERPENTS Team. Only two materials were utilized by the current team, and those are fiberglass with resin, and a spacesuit material. Table 3 shows the relevant material properties for the fiberglass and the pressure rated spacesuit material. The fiberglass material properties were provided by the fall 2010 SERPENTS team. Uncertainty in the material properties of the spacesuit material exists due to the specialized nature of the materials. Research and testing is necessary to determine the needed material properties. (Brown and Pinkston 15)

Table 3: Material Analysis

Material Analysis					
Material	Location	Modulus of Elasticity (psi)	Thermal Conductivity $\left(\frac{W}{m \cdot K}\right)$	Ultimate Strength (psi)	Yield Strength (psi)
Fiberglass and Resin	Sidewall	$11.5 \cdot 10^6$	1.3	$500 \cdot 10^3$	N/A
Outer Skin	Outside	Unknown	Unknown	Unknown	Unknown

As the materials the team worked with are not metallic, corrosion will not occur in the materials, and the materials will not cause corrosion in the metal parts they connect with. Fatigue is likely to occur in the fiberglass strips, due to the cyclic loading of the bulkheads, and further analysis is needed to determine the life of the strips. Sharp particulate is likely to cause punctures or rips in the spacesuit material, but as the strength of the material is unknown, further tests will be required to determine the strength of the material. (Brown and Pinkston 16)

6.4 Technical Analysis (Michael Pinkston)

The following technical analysis was done during the fall 2011 semester by the SERPENTS Team. A column buckling analysis was used to determine the buckling force of the fiberglass strips, since the effective length of the fiberglass strips was changed from the previous teams design. Figure 12 shows the steps taken to determine the buckling force. The buckling force was determined to be 1.58 lbf. (Brown and Pinkston 16)

Givens:

$b := 0.5in \quad h := 0.02in \quad L := 4.9in$

$E := 11.5 \cdot 10^6 psi$ **Approximation for fiberglass, taken from Ben Gasser's analysis**

Modified Column Buckling:

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

$$P_{cr} := \frac{\pi^2 E \cdot I}{L^2} \qquad P_{cr} = 1.576\, lbf$$

Figure 12: Technical Analysis done in MathCAD
Work Provided by M. Pinkston

6.5 Functional Flow Block Diagram (Mallory Brown)

Two Function Flow Block Diagrams (FFBDs) were created for the SERPENTS project. The first (as shown in Figure 13 is for the completed final SERPENTS hardware. This project is for the mission described in the ConOps. The second FFBD (shown in Figure 14) was created for the current peristaltic body segments constructed by the 2011-2012 SERPENTS Team.

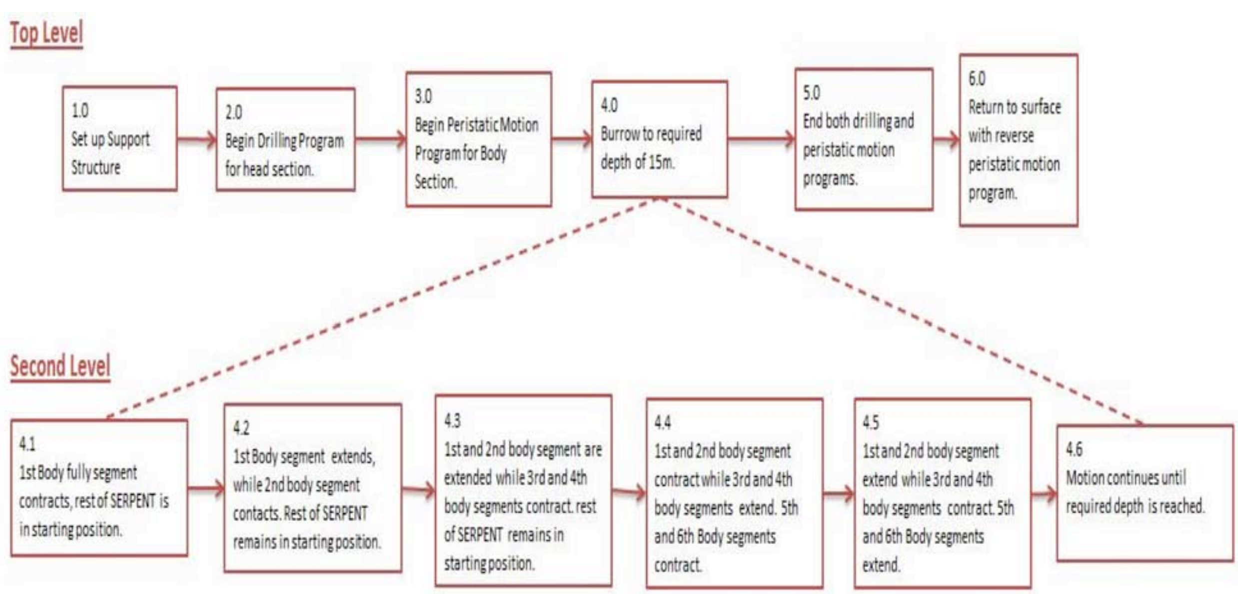

Figure 13: Full System FFBD
Photo Provided by M. Brown

For the completed system, the following steps were outlined for the running of the hardware.

1. The mission personnel set up the support structure in order to provide power, navigation, and structural support for the SERPENTS while in operation.
2. The SERPENTS operator begins the drill program written to run the head section of the SERPENTS.
3. Once the SERPENTS is securely in the ground, the operator will begin the peristaltic motion program to move the active body segments.
4. The SERPENTS then burrows to the required 15 m depth, collecting the soil samples at even intervals.
5. Once at the mission depth, the SERPENTS stop all running programs (both drilling and peristaltic motion).
6. The SERPENTS then reverses the peristaltic motion program and returns to the surface with the collected soil samples.

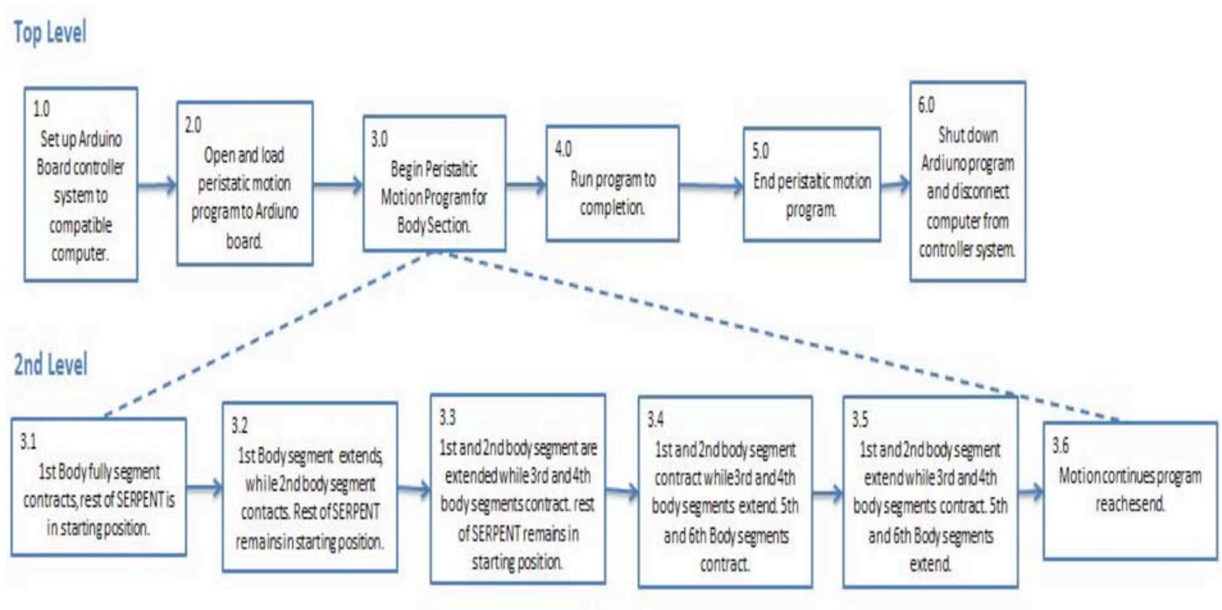

Figure 14: Active Body Segments FFBD

Photo Provided by M. Brown

For the active body segments, the following steps were outlined for the running of the hardware.

1. The operator connects the Arduino board controller system to a compatible computer and if not loaded, downloads the Arduino program from the company homepage.
2. The operator opens the peristaltic motion file (as seen in Appendix C) created by Nathan Wiseheart.
3. The operator runs the program, which sends the signal to the Arduino board and actuator controller boards.
4. The program then runs to the completion of the program.
5. Once the program completes the programmed movements, the program will end.
6. The operator then closes the Arduino program on the computer and disconnects from the controller system.

6.6 Interface Requirements (Mallory Brown)

The 2011-2012 SERPENTS Team utilized an N^2 Diagram to analyses the interfaces in the system. As seen in Figure 15, there are 4 main interfaces within the system: the operator, the computer hooked to the Arduino board, the Arduino control system, and the linear actuators of the SERPENTS.

Operator	1		
6	Computer	2	
	5	Arduino Board	3
7		4	Linear Actuators

Figure 15: N^2 Diagram

Photo provided by M. Brown

The following interactions occurred in the system:

1. The operator instructs the computer to run the program that runs the SERPENTS's actuators. The operator can also input need programs (change the peristaltic motion program) in this interface.
2. The computer sends the inputted program to the Arduino board controller system.
3. The Arduino board commands the actuators to move an ordered amount.
4. The actuators report the distance moved to the Arduino, so the board can report

accordingly. The actuators send back an error if they cannot complete the program.

5. The Arduino board reports the change in length experienced by the actuators to the computer.
6. The computer displays the results of the run program to the operator.
7. The operator can see the actuators moving the set distance.

7. Final Design and Fabrication (Mallory Brown, Michael Pinkston, Johnny Dingler, Nathan Wiseheart, Randy Brackins)

7.1 Product Design Specifications (Mallory Brown)

During the fall semester of 2011, the SERPENTS Team completed a Product Design Specification (PDS) to define the specific function and operation of the SERPENTS. No changes were made to the document during the spring 2012 semester. The PDS was separated into two major sections: an update on the information discussed in the CDD and a description of the functions of the product. The function and operational specifications discussed in this document were market requirements, functional requirements, physical requirements, and support requirements for the SERPENT. The support requirements included life cycle issues, storage and transportation of the SERPENT when not in use, and the legal and social ramifications of the project (Brown and Pinkston 15). The full PDS document can be found in Appendix (B). The revision number of the PDS shown in Appendix C is Revision 00.

7.2 Product Descriptions and Drawings (Mallory Brown)

The overall appearance of the body segments of the SERPENTS is of an extended cylinder. The body section is made up of six identical segments with seven bulkheads. There is a whole in both ends of the bulkheads while allow the actuator cabling to run. As shown in Figure 16 (without the fiberglass strips) and Figure 17 (with the fiberglass strips), the internal components consist of the actuators, bulkheads, retainer rings, and assorted fasteners. Around the internal components is the plate of fiberglass and the external skin.

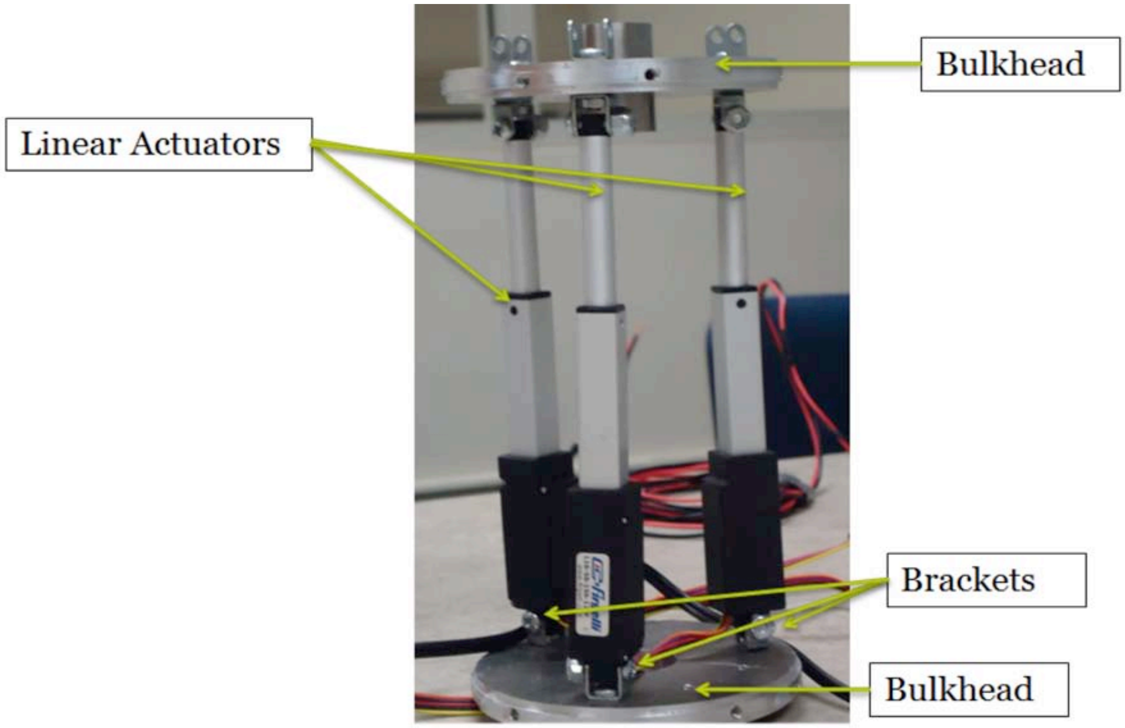

Figure 16: Internal Components Layout (without fiberglass strips)

Photo provided by M. Brown

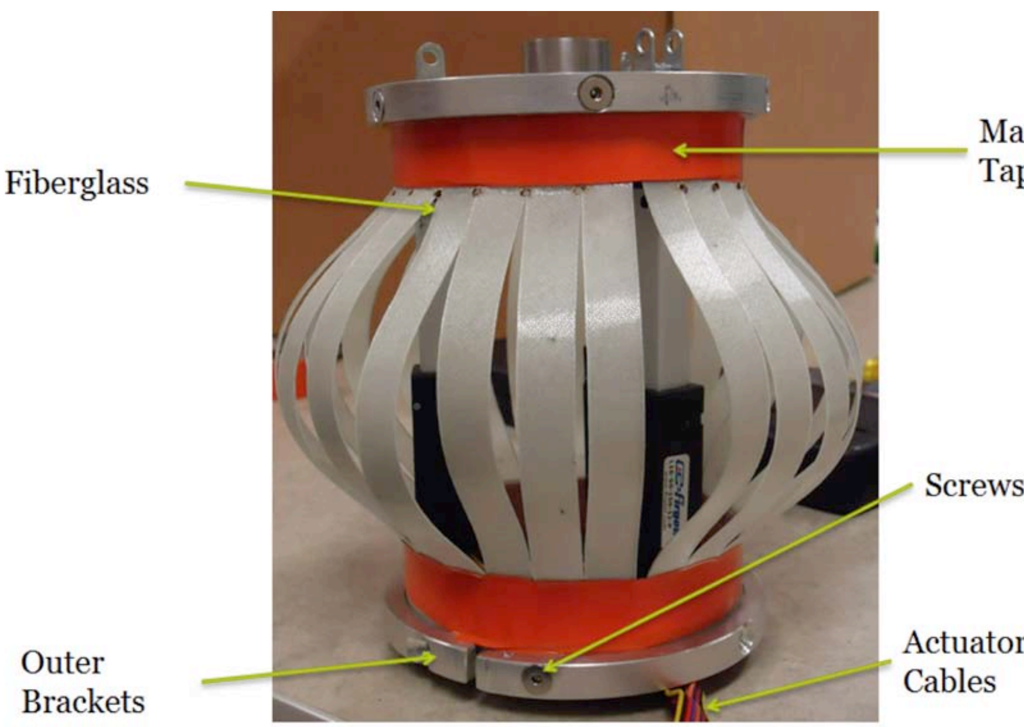

Figure 17: Internal Components Layout (with fiberglass strips)

Photo provided by M. Brown

7.3 Part Specification (Mallory Brown)

The complete list of all parts used in the body segment assembly can be seen in Table 4. How the specific parts fit together in the final assembly can be seen in Figures 37-42 in Appendix E. The wiring assembly can be found in section *7.5 Assembly and Installation Methods*.

Table 4**:** Part Specification

Part	Purpose	Number in Assembly	Material	Manufacturing Process / Assembly	Location
wires	connects the LAC controllers and Arduino board to the linear actuators		copper wires	This part was bought fully constructed. The wires were soldered into place during assembly.	body segment, wiring board
breadboard	Complete the wiring of the electronics.	1	computer board	This part was bought fully constructed. The wires were soldered into places on the breadboard during assembly.	wiring board
replays	Complete the wiring of the electronics.	6	computer board	This part was bought fully constructed.	wiring board
120 Volt AC plug	provide power to the system	1	plug	This part was bought fully constructed.	wiring board

Table 4: Part Specification (continued)

Part	Purpose	Number in Assembly	Material	Manufacturing Process / Assembly	Location
Bulkhead	Structural support of individual segments and overall body section.	7	Aluminum alloy	machined - milled	body segment
Brackets	connection of actuators to bulkheads	36	Aluminum alloy	machined	body segment
Linear Actuators	Provide the peristaltic motion to the SERPENTS.	18		this part was bought fully constructed from Firgelli.	body segment
M8x1.25 bolts	attach the brackets to the bulkheads	36	Aluminum alloy	machined	body segment
Locknuts	attach the brackets to the actuators	36	Aluminum alloy	machined	body segment
Fiberglass Strips	Apply the force of the actuators upon the sides of the tunnel.	6	fiberglass	composite layup	body segment
retainer rings	attach the fiberglass to the segment	14	Aluminum alloy	machined	body segment
screws	attach retainer rings to bulkheads	28	Aluminum alloy	machined	body segment
skin	protect internal components from external hazards	1	pressure suit material	this part was bought fully constructed from Seattle Fabrics.	body segment
Arduino board	provide and run the peristaltic program for the system	1	computer board	this part was bought fully constructed.	wiring board
LAC controller boards	controls the speed, length of expansion/contraction	6	computer board	this part was bought fully constructed from Firgelli.	wiring board

7.4 Manufacturing Methods (Johnny Dingler)

7.4.1.1 Definitions

Layup - A process of laminating the fiberglass into the desired shape, from 1 to ∞ layers.

Ply/plies - Each layer of fiberglass is referred to as a "ply". 4 ply layup = 4 layers of fiberglass.

Resins/epoxies - The "glues" that hold the fiberglass together. Resins/epoxies contribute no strength to the part.

BID Fiberglass - BID implied bi-directional, fibers running ninety degrees to each other. BID is very strong in two directions because the concentration of "toes" is in the two directions.

Mold release – A product used to keep fiberglass from sticking to a mold or form.

7.4.1.2 Forming the Fiber Glass

The following is a list of steps that were used to form the fiberglass panels which were tested for the team project. Manufacturing of the fiberglass was performed in the Reliability laboratory located in Van Braun Research Hall on the campus of UAHuntsville. The manufacturing process was performed by the SERPENTS team with direct supervision of Greg Doub and Nathan Rigoni. Dr. Bill Wessels was also very helpful with setting up the initial meeting and coordinating time the laboratory could be used.

Area Preparation: A clean surface area was prepared prior to starting the fiberglass layup. For this layup, an aluminum plate was used to establish a smooth uniform backing for the fiberglass to be applied to. The Aluminum plate was fist cleaned using alcohol to remove and dirt or oil on the surface. Once the plate was clean, a dam of tacky tape/putty was applied around the edges of the plate (Figure 18). This served two functions; the first was to help maintain the resin and other material inside the work area. The second and primary function was to help achieve a vacuum seal over the fiberglass while it was curing. NOTE: Proper ventilation and/or air filtration must be used when working with cleaning solvents.

Mold Release: Once the area was cleaned, the mold release and a sheet of Teflon to the pre-cleaned area. This allows for easy release of the fiberglass from the surface it was applied on.

Resin and Hardener: After preparing the area, the resin and hardener were then mixed. For this application, 635 resins and hardener, form from US composites, with a 3:1 ratio was used. The Resin and hardener were measured and mixed per the suppliers instructions. With the resin and hardener properly mixed, it was then applied over mold release and Teflon. The resin is pour directly and evenly on the prepare surface to help achieve a good uniform application for the resin to the fiberglass mat that will be applied next. NOTE: Proper ventilation and/or air filtration must be used when working with resins. Proper gloves should also be used to protect ones hands and exposed skin.

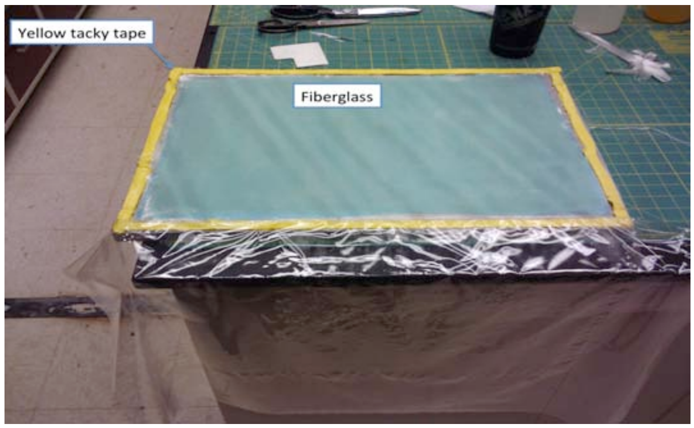

Figure 18: Fiberglass layup on the aluminum plate.
Photo provided by J. Dingler.

Laying the Fiberglass: With the resin applied over the prepared area, the first layer of fiberglass mat was applied. Any air bubbles or wrinkles were smoothed out using a rubber blade and slight amount of pressure to force the fiberglass mat tight to the smooth surface. The bubbles and wrinkles can also be removed using a wooden, plastic or rubber roller. Additional resin was applied to any area for the fiberglass mat that appeared white.

After the fiberglass mat appeared to be smooth and uniform, additional resin was poured over the first fiberglass layer. The second layer of fiberglass mat was then applied over the first layer and once again the air bubbles and wrinkles were removed. This process was repeated until the desired number of layers was achieved. NOTE: Proper ventilation and/or air filtration must be used when laying the fiberglass. Proper gloves should also be used to protect ones hands and exposed skin.

Vacuum bagging: A piece of plastic material was cut a little larger than the size of the aluminum plate. This plastic was used to cover the fiberglass and was secured to the tacky tape. This allowed for the air tight seal between the aluminum plate and the plastic. Prior to placing the plastic over the fiberglass, a sheet of *Peel- ply*, impregnated with Teflon, was place over the fiberglass and resin material. A sheet of foam was then applied over the *Peel-ply*. The Peel-ply allows for easy remove of the fiberglass, acting as a mount release. The foam is placed between the peel-ply and plastic bag to allow for even distribution of the vacuum surface. A vacuum attachment was placed on the plastic (Figure 19) and the vacuum was turned on to applied a vacuum of approximately 25 PSI.

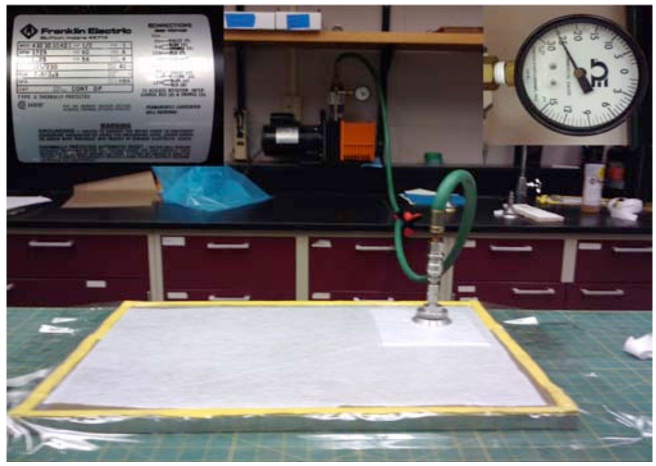

Figure 19: Vacuum applied to the fiberglass

Photo provided by J. Dingler.

Curing Process: The fiberglass remained on the form with the vacuum pump running for a minimum of 30 minutes. Once the proper vacuum was achieved, the pump was shut off and the fiberglass remained under vacuum pressure for 24 hours to allow for full cure.

After the required cure times, the fiberglass was removed from the form.

7.4.2.2 Sizing the fiberglass

Shearing**:** Shearing works well for cutting thin fiberglass less than 0.050” thick. Again the fiberglass must be well supported while shearing to avoid splintering. The shearing process was used for sizing the fiberglass pieces for this project. An industrial paper cuter was used to cut each fiberglass to the desired length and width. Refer to Figure 20 for the shearing process. NOTE: Proper ventilation and/or dust mask must be used when working with fiberglass. Proper gloves should also be used to protect ones hands and exposed skin.

Cutting/sawing: A fine-toothed or diamond hack saw blade works well for cutting fiberglass. One must support the back side of the fiberglass when cutting through to avoid splintering of the fiberglass as the blade comes through the back. It is also advisable to place tape on each side of the fiberglass to reduce splintering. NOTE: Proper ventilation and/or dust mask must be used when working with fiberglass. Proper gloves should also be used to protect ones hands and exposed skin.

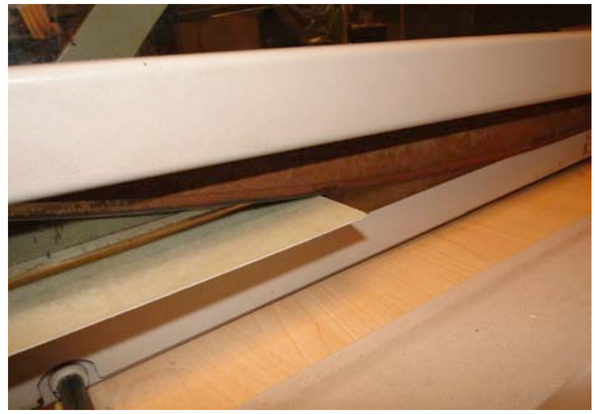

Figure 20: Shearing the Fiberglass

Photo provided by J. Dingler.

Drilling: Drilling was used for manufacturing the fiberglass pieces for this project. A sharp bit or diamond coated bit must be used set at on very slow speeds when drilling. One must not apply any presser to the bit. The bit should be allowed to do the work and pull itself through the material. NOTE: Proper ventilation and/or dust mask must be used when working with fiberglass. Proper gloves should also be used to protect ones hands and exposed skin.

Machining Fiberglass: Most fiberglass applications require tungsten carbide tooling for effective machining. Fiberglass is generally *very* abrasive and capable of destroying cutting edges on standard high speed steel tooling in a manner of seconds.

Sanding: A light amount of sanding was used to remove sharp edges and burrs following the cutting and drilling of the fiberglass pieces. The sanding was done by hand but could have been performed using an orbital sander. NOTE: Proper ventilation and/or dust mask must be used when working with fiberglass. Proper gloves should also be used to protect ones hands and exposed skin.

7.5 Assembly and Installation Methods (Nathan Wiseheart)

The assembly took place in the garage of Nathan Wiseheart at 16822 Woodhaven Drive, Athens, Al. 35613. The assembly of the current design was fairly simple and was done with a screwdriver and a nut driver for the metal components such as the brackets and bulkheads. However, the electronics assembly was more in depth and required some soldering.

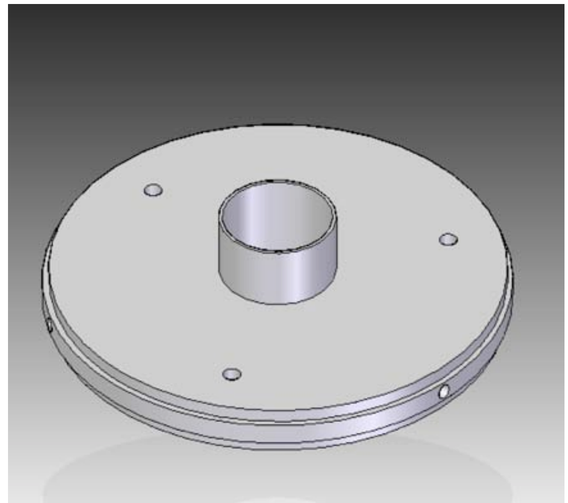

Figure 21: End Bulkhead

CAD drawing provided by N. Wiseheart

1. The Assembly starts by getting the End Bulkhead as shown below in Figure 21:
2. The Actuator Brackets are then mounted to the bulkheads in their designed orientation so the actuator is at the correct angle when attached (Figure 22).
3. The Actuators are connected with a M8x1.25 machined bolt and nut to the actuator brackets that are now connected to the bulkhead (Figure 23).
4. Once Step 3 is complete, then the other bulkhead is attached to the actuators via the brackets and M8x1.25 bolts with locknuts (Figure 24).
5. Once Steps 1 through 4 are complete, repeat each step starting with number 1 so the next segment of the SERPENTS will be assembled and attached to the second bulkhead of the already assembled segment 1.
6. After all segments are assembled, all linear actuators are to be wired by soldering and then connected to the LAC controller board for each segment.

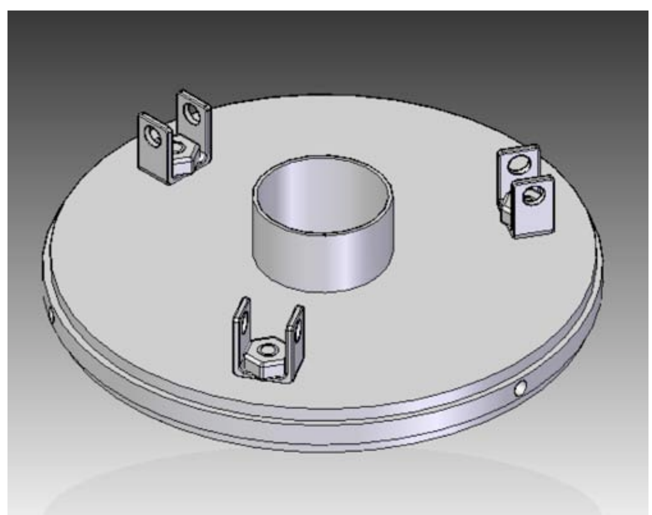

Figure 22: End Bulkhead with Brackets

CAD drawing provided by N. Wiseheart

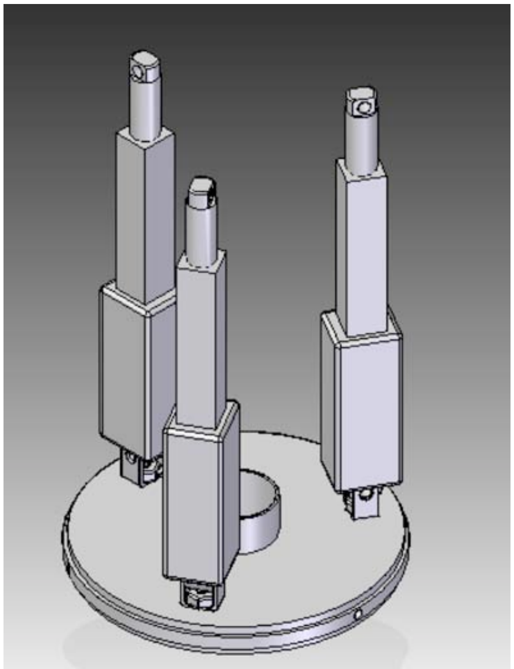

Figure 23: End Bulkhead with Actuators
CAD drawing provided by N. Wiseheart

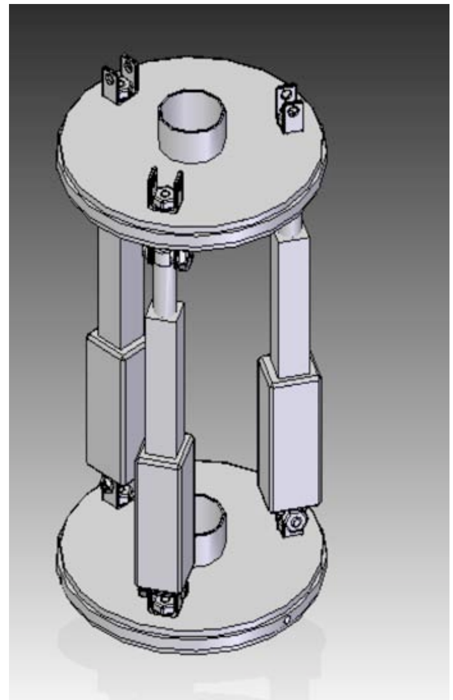

Figure 24: Interior Components
CAD drawing provided by N. Wiseheart

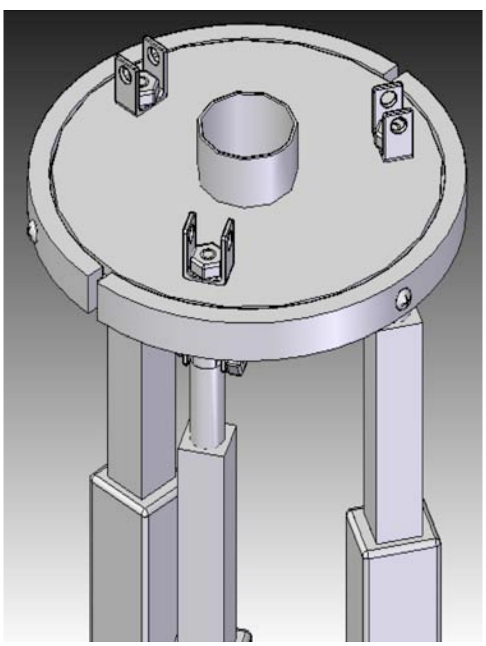

Figure 25: Upper Bulkhead
CAD drawing provided by N. Wiseheart

Figure 26: Complete Segment
CAD drawing provided by N. Wiseheart

7. After all segments are assembled, the retainer ring halves are to be installed on each bulkhead so the fiberglass strips can be attached to each segment. The retainer rings are held on with screws as shown below in Figure 25.
8. Once the retainer rings are applied to the two bulkheads per section, do not fully tighten the screws holding them on all the way down. Just start the screws so there is still a gap between the retainer ring and the bulkhead for the fiberglass to slide into. Once the fiberglass is slid into place between the bulkheads and the retainer rings, the rings are to be tightened down as much as possible in order to hold the fiberglass segment in place. (Figure 26)

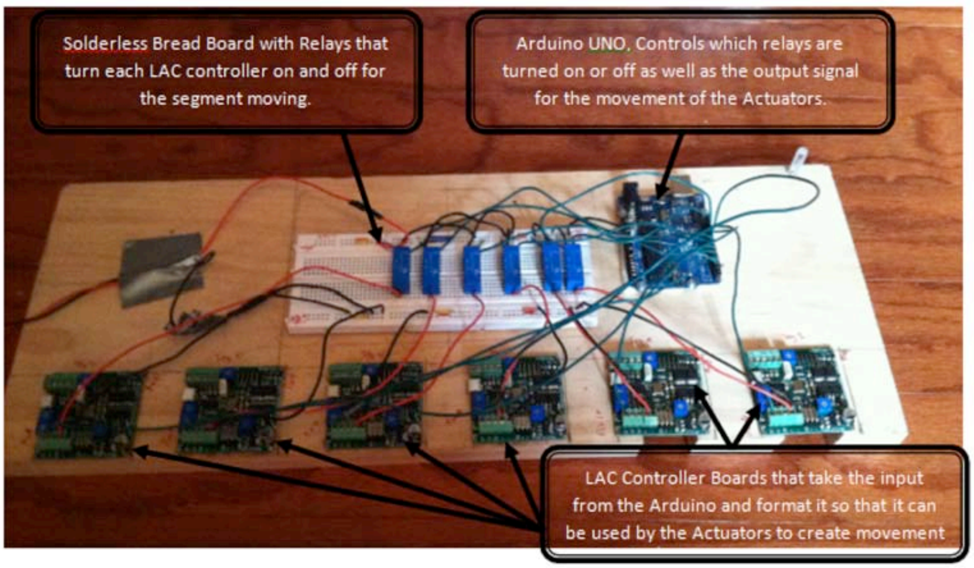

Figure 27: Control Board

Photo provided by N. Wiseheart

Once all the segments are complete and all the fiberglass spring members are installed, the segments labeled 1 through 6 should be connected to all controllers 1 through 6 with the five pin servo connector. Once the SERPENTS assembly is completed and the segments are hooked up to the corresponding LAC controllers on the main control board. Figure 27 shows the setup of all the controllers with the Arduino and solder-less breadboard. A schematic to show how the breadboard, Arduino, and LAC's are connected is shown in Figure 28.

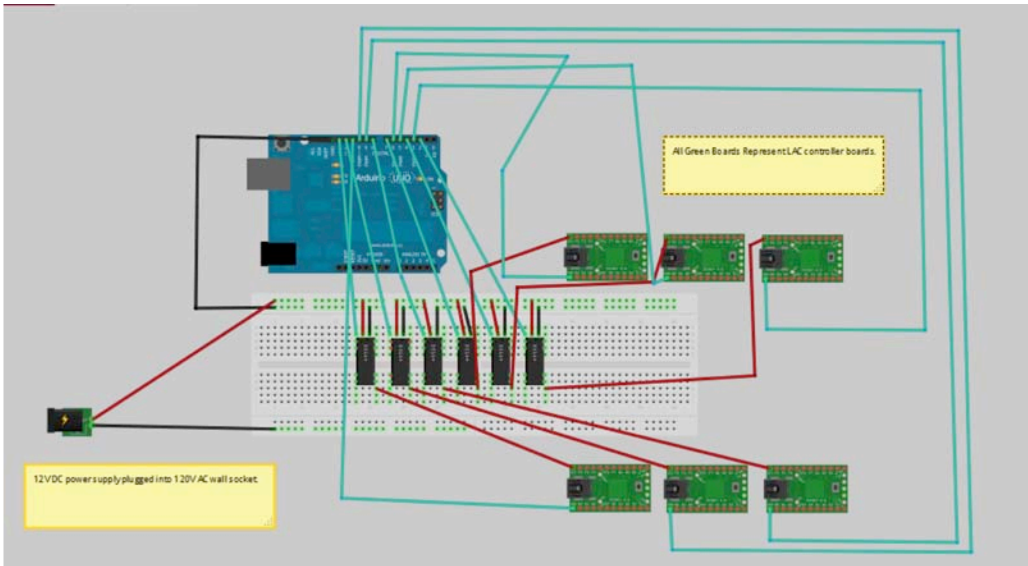

Figure 28: Wiring Diagram

Photo provided by N. Wiseheart

In Figure 29, the Green Boards represent the LAC controller boards for the SERPENTS Electronics System. This wiring diagram shows how the Arduino is connected to the solder less bread board and then connected to the LAC controller boards. This is how the Circuit is wired in order for the SERPENTS to work properly.

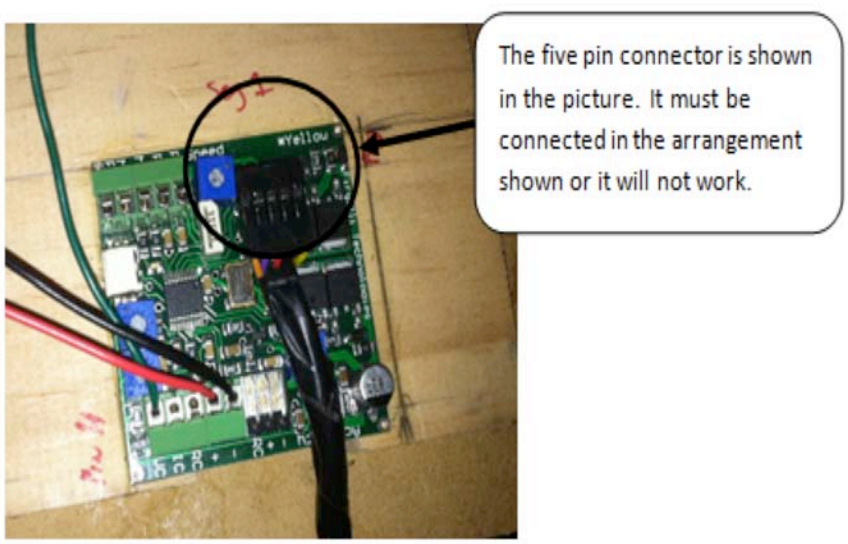

Figure 29: LAC Controller for Firgelli Actuator

Photo provided by N. Wiseheart

7.6 Operation and Maintenance Instructions (Nathan Wiseheart)

To operate the hardware, all that needs to be done is the five pin actuator connectors are to be connected to the control panel LAC's as shown in Figure 27. Once this is done, the Arduino is to be connected to a computer with Arduino Software via the USB cable and the software sketch named "Use_with_LAC_from_Firgelli_using_PWM" is to be opened. Once the sketch is opened, the 120 Volt AC plug that converts the voltage to 12 Volts DC and 1.5 amps is to be plugged in.

Figure 30: Up Arrow
Photo provided by N. Wiseheart

As soon as the Power source is plugged in, the Arduino sketch is to be uploaded by pushing the upload button which is shown in Figure 30. Figure 29 shows the five pin actuator connector in the proper orientation. The connector must have the five wires from left to right in the colors listed: orange, purple, red, black, and yellow.

7.7 Verification Tests (Randy Brackins)

During the 2011 spring semester, the team tested the modulus of elasticity and tensile strength of the fiberglass stripes to determine if they were capable of supporting the 66N as specified in the system requirements.

For the Long align fibers:

- *Modulus of Elasticity in longitudinal direction (E_{cl}):* $E_{cl} = E_m*V_m + E_f*V_f$
- *Modulus of Elasticity in transverse direction (E_{ct}):* $1/E_{ct} = V_m/E_m + V_f/E_f$

Therefore: $E_{cl} = \eta_0\eta_L V_f E_f + V_m E_m$

$\eta_L = 1 - 2/\beta L*\tanh(\beta L /2)$
$\beta = [8 G_m/(E_f D^2 \ln(2R/D))]^{1/2}$

The following variables were used in the calculations:
E_f – modulus of elasticity of fiber material;
E_m – modulus of elasticity of matrix material;
G_m - shear modulus of matrix material;
η_L – length correction factor;
L – fibers length;
D – fibers diameter;
2R – distance between fibers;
η_0 - fiber orientation distribution factor.
η_0 = 0.0 align fibers in transverse direction
η_0 = 1/5 random orientation in any direction (3D)
η_0 = 3/8 random orientation in plane (2D)
η_0 = 1/2 biaxial parallel to the fibers
η_0 = 1.0 unidirectional parallel to the fibers

Figure 31: Experimental Apparatus

Photo provided by R. Brackins

As shown in Figure 31, the following data (in Table 5) was collected from the experimental apparatus. Deflection with hanger only =-0.1147

Table 5: Experimental Data

Newton	Loaded	Unloaded	Thickness/inches
0.5	-0.1529	-0.1731	.037
2.5	-0.3159		.037
.0823	-0.1147	-0.1298	.037
0		-0.0527	.037

Where: L= 5inches and W=1.051 inches

Following the determination of the modulus of elasticity, the experiment was conducted to determine the tensile strength of the fiberglass. As shown in Figure 32, the strips were laid flat upon the experimental apparatus and a force was applied.

Tensile Strength

- *Tensile strength of long-fiber reinforced composite in longitudinal direction:*
  $\sigma_c = \sigma_m * V_m + \sigma_f * V_f$

Where:|
σ_c, σ_m, σ_f – tensile strength of the composite, matrix and dispersed phase (fiber) respectively.

- *Tensile strength of short-fiber composite in longitudinal direction*
  (fiber length is less than critical value L_c)
  Therefore $L_c = \sigma_f * d / \tau_c$

Where:|
d – diameter of the fiber;
τ_c –shear strength of the bond between the matrix and dispersed phase (fiber).

$\sigma_c = \sigma_m * V_m + \sigma_f * V_f * (1 – L_c/2L)$

Where: L – length of the fiber

Figure 32: Experimental Apparatus

Photo Provided by R. Brackins

- *Tensile strength of short-fiber composite in longitudinal direction*
  (fiber length is greater than critical value L_c) : $\sigma_c = \sigma_m * V_m + L * \tau_c * V_f / d$

The small ribs failed to meet customer requirements however, the wider ribs were able to withstand the requirements by withstanding 368 N or ~ 82.6lbf (as seen in Table 6). The graph generated from the experimental can be found in Figure 33. Therefore it would be advisable to use the wider of the ribs at the 0.037 inches thickness. This would allow the correct amount of flex as well as maintain the correct stiffness to allow for proper loading.

Table 6: Experimental Data for Tensile Strength

Modulus of Elasticity				**Buckling**		
L =	5	in		Le =	2.5	in
x =	2.5	in		Pcr =	6.9	lb
b =	1.051	in		N =	12	
t =	0.037	in		Pcr,tot =	82.6	lb
I =	4.43636E-06	in^4			368	N
P (lb)	y (in)	E (psi)				
0.185	-0.1147	946783				
0.297	-0.1529	1140226				
0.859	-0.3159	1596194				
0.297	-0.1731	1007167				
0.185	-0.1298	836641				
	Average	982704.4				
	Random Unc	273570.3				
	% Uncertainty	0.278385				

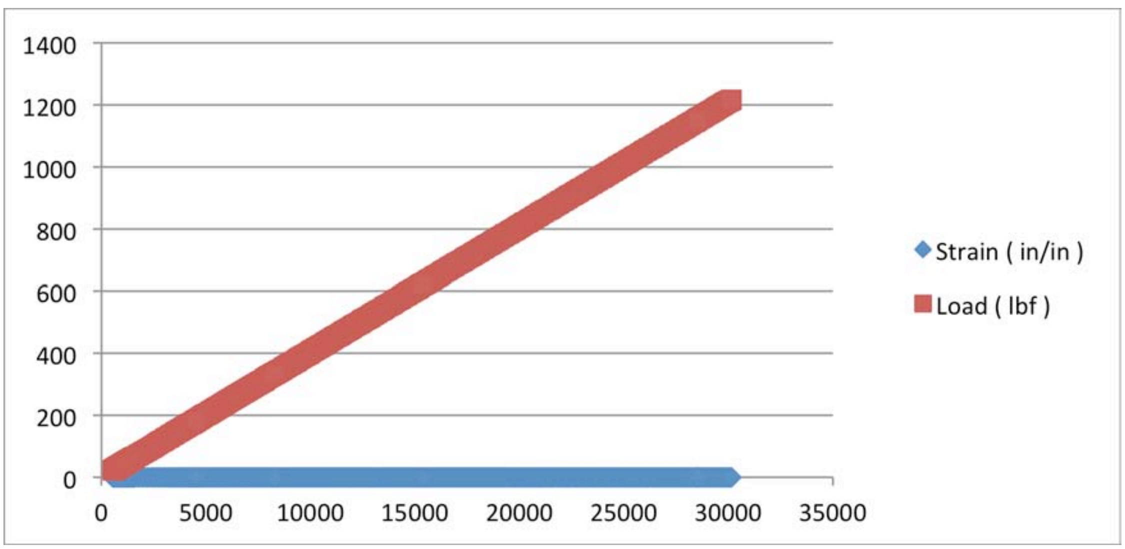

Figure 33: Experimental Data

Work provided by R. Brackins

7.8 Requirements Verification Matrix (Mallory Brown)

The requirements verification matrix referred to in this section can be found in Table 6 in Appendix F. Out of the nineteen final requirements for the SERPENTS project, six of the requirements have been fully met. Out of the thirteen remaining requirements, four of which are the responsibility of the LA Tech SERPENTS Team, two of which are a joint requirement for both teams, and seven of which are requirements for the UAH SERPENTS Team. For requirements numbers 4, 6, 13, and 14, were not meet because they were not the responsibility of this team. For requirements numbers 8 and 16, the requirements were not met due to further testing needing to be done (# 16) and because the design stage where the requirement is to be met has not occurred yet (#8). For requirements numbers 1, 7, 9, 10, 12, 18, and 19 were the responsibility of the UAH SERPENTS Team.

Requirement number #1 was not met because further testing, including a full systems test to be performed at the Kennedy Spaceflight Center (KSC), needs to be conducted to be met. The requirement is partially met in that the skin abrasion test and the actuator test have been verified. Requirement # 7 has not been met due to a water test needing to be conducted in order to verify that the material is water-tight. Requirement #9 was not met because in order to verify this requirement, a test bed deep enough to allow a vertical testing of the hardware needs to be found, and a test run to verify the requirement. Requirement #10 was not met for the same reason as #9, in order to verify if it can survive multiple missions, the hardware needs to be tested multiple times burrowing vertically, not horizontally. Requirement #12 was not met because it was decided early in the conceptual design phase to focus more on the physical testing of the hardware and materials would be more beneficial than theoretical modeling of the system. Requirement #18 was not because the team has not yet traveled to KSC for the full hardware testing. Requirement #19 has not been met because after actuator testing, it was found they the brackets were not in need of redesigning.

7.9 Safety (Mallory Brown)

The operation and maintenance of the SERPENTS shall be completed by fully trained staff in order to avoid accidental injuries. The safety evaluated by the 2011-2102 SERPENTS team included accidental drops, pinch points, manufacturing accidents, assembly accidents, and testing hazards. The Hazard Risk Assessment Ratings (United States Air Force Safety Centre) for the health risks and operational procedures to avoid those risks are as follows:

7.9.1 Accidental Drops

The Hazard Risk overall rating is 19 (Hazard Frequency of Occurrence Rating: Occasional, The Hazard Consequence of Occurrence Rating: Marginal). The body segments constructed during this project timeline are cylindrical in geometry, thus leading to a device prone to rolling. Therefore, all precautions to avoid the SERPENTS rolling of a surface are to be taken. Due to the high chance of injury due to drops, the device will carry warning labels about the weight and potential for drops. The operators will also be instructed that to lift the completed device, two people will be required to lift it (to avoid drops but also other health problems associated with heavy objects i.e. back and spinal problems). Operators will also not carry the device when needing to move the SERPENTS across the building; a cart will be used to move it to avoid the above stated problems. A protocol will be in place when working on the SERPENTS that all personnel will wear hard covered shoes when working on the SERPENTS. Whenever the SERPENTS are being maintenance or otherwise worked with, the device will be restrained to the workstation to avoid the SERPENTS accidentally roll off the table top (Brown and Pinkston 19-20). These precautions will also be taken during manufacturing and assembly.

7.9.2 Pinch Points

The Hazard Risk overall rating is 11 (Hazard Frequency of Occurrence Rating: Remote, The Hazard Consequence of Occurrence Rating: Negligible). The risk assessment for the pinch points is much lower than the risk of accidental drops as the risk of pinching can only occur when the protective outer skin is breeched to allow for maintenance. Otherwise, the thickness of the outer skin provides enough distance between the metal beams of the actuators and a person's finger. When maintenance is required the technician will complete turn off power from the SERPENT (to avoid the actuators from accidentally contracting). There will also be warning labels posted along the body segments to warn of the possible danger (Brown and Pinkston 19-20). During the assembly phase, all precaution will be observed to prevent any accidents. During this stage of develop, the protective skin is not yet on the hardware, leaving the risk of pinches an ongoing hazard. When working on or with the SERPENTS, personnel will only handle the actual hardware when absolutely necessary.

7.9.3. Miscellaneous Other Hazards

Due to the linear actuators used in the design, electrical power runs through the SERPENTS will in operation. The Hazard Risk overall rating for accidental shocks is 20 (Hazard Frequency of Occurrence Rating: Improbable, The Hazard Consequence of Occurrence Rating: Negligible). In order to avoid these hazards, only qualified personnel will handle the SERPENTS. Also, there will be absolutely no handling will occur when the SERPENTS is in operation.

7.10 Reliability (Mallory Brown)

The failures of the SERPENTS system were evaluated through the use of the Fault Tree Diagrams (FTAs). The first FTA was created for the body segments designed and fabricated during the 2011-2012 project timeline. As seen in Figure 34, there were three major ways that the body segments could fail: a failure in the electronics, the skin rips open exposing the internal components, and an actuator breaks.

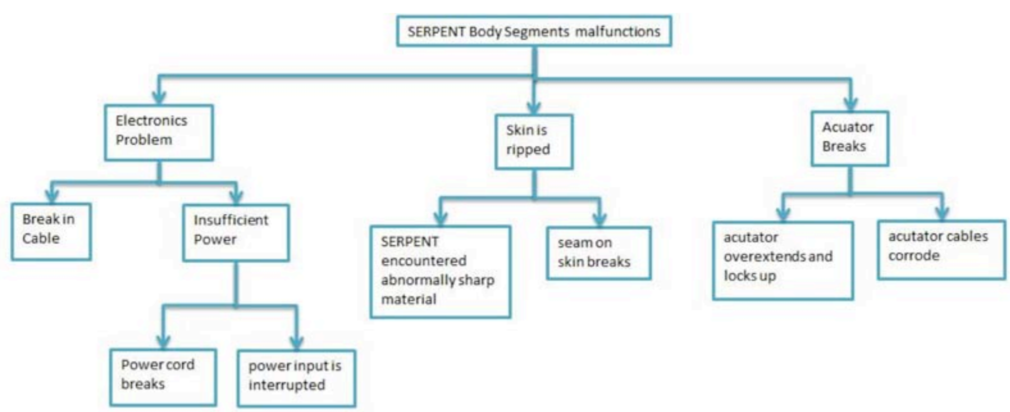

Figure 34: Body Segments FTA

Photo provided by M. Brown

The other FTA done for the SERPENTS was for the overall project as defined in the Concept of Operations. As seen in Figure 35, the main failures in the mission would be: deployment of the SERPENTS from the lander or the carrying case, support structure breakage, head section breaks.

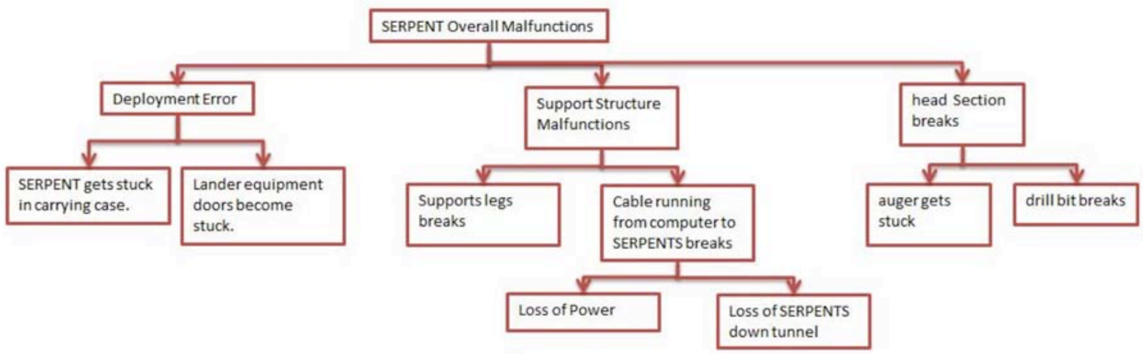

Figure 35: Full System FYA

Photo provided by M. Brown

7.11 Final Costs / Budget (Michael Pinkston)

The following table (Table 7) breaks down the cost incurred during the 2011 spring semester by the SERPENTS Team.

Table 7: Final Cost Analysis

Parts				
Part	**Vendor**	**Quantity**	**Cost**	**Team Cost**
Controller Boards	Firgelli	13	$520.00	
Linear Actuators	Firgelli	6	$280.00	$208.40
Outer Skin	www.seattlefabrics.com	4 yards	$86.00	$86.00
Manufacturing				
Type	**Manufacturer**	**Quantity**	**Cost**	**Team Cost**
Composite Layup	UAH Reliability Lab	1	$51.12	$51.12
Testing				
Type		**Quantity**	**Cost**	**Team Cost**
Actuator Test		3	$10.00	$0.00
Electronics Test		3	$15.00	$0.00
Full System Test		Unfinished	$50.00	$0.00
Engineering Effort				
Type		**Quantity**	**Cost**	**Team Cost**
Full System Setup		1	$1012	

7.12 Product Disclosure Form (Mallory Brown)

The 2011-2012 SERPENTS Team did not complete a Product Disclosure Form this semester. After discussing the possibility of signing on with the Office of Technology Commercialization on 6 April 2012, it was decided that there was nothing about the work done by this team that needed to be protected. Without signing the form, the research on this project could be more easily continued next semester. It was also decided that since NASA was not seriously working towards a patent on this research, there was no real pressing need for the team to patent independently.

7.13 Team Poster (Mallory Brown)

The following team poster was created for the 2011 – 2012 SERPENTS UAH Team to promote and educate about the work being done by this team. The poster can be seen in Figure 36 in Appendix G.

8. Problems and Solution (Michael Pinkston)

The following sections detail the problems encountered over the course of the spring 2012 semester and the steps taken by the SERPENTS Team to correct them.

8.1 Parts Procurement (Michael Pinkston)

To ensure that every part that needed to be ordered would be available when needed, each part was ordered as soon as possible to ensure that any delays in processing or shipping could be taken into consideration, and the parts would arrive before they were needed.

8.2 Technical Analysis (Michael Pinkston)

As the team focused on the construction of the SERPENTS, as well as material analysis, no new technical analysis was conducted this semester.

8.3 Manufacturing (Michael Pinkston)

One problem that arose during the manufacturing of the composite strips was arranging favorable work times with the UAH Reliability Lab. This was solved through a couple team members working exclusively with the Lab, and also ensured that everyone involved was on the same page, and nothing needed to be re-explained.

8.3 Assembly (Michael Pinkston)

During assembly, problems with the full systems testing arose, involving the power consumption of the individual sections. This was solved by taking the necessary time to fully investigate the issue, and to find and eliminate everything that was causing problems. By stepping back and evaluating the problem exclusively, it prevented the team from spending unnecessary amounts of time troubleshooting the entire system.

8.4 Verification Tests (Michael Pinkston)

During the full system verification test, a controller board which controlled a section of the SERPENTS went missing. This was solved by first searching for the missing board, and then by ordering more controller boards. Another problem arose when a few linear actuators which had not previously been in the teams' possession were not functioning. This was solved by contacting the company which makes the actuators and ordering several more.

8.6 Lessons Learned (Michael Pinkston)

During the course of the semester, the team learned to act professionally in every interaction. As this is an ideal time to practice the same professionalism that is needed in the workforce, working with vendors and manufacturers in a professional manner provides good practice for similar encounters later in life. Acting professionally through any kind of environment, whether working with someone who does not understand what is needed, or with someone who is hostile towards the project, shows that the other person is taken seriously, and can defuse tense situations and provide more favorable results rather than making the situation worse.

Working early and often is another lesson the team learned throughout the project. By putting in work early, it allowed time for solving the problems that will inevitably arise, and provided a cushion of extra time to ensure that the product is of the highest quality.

9. Conclusions (Mallory Brown)

9.1 Summary (Mallory Brown)

The prototype created during the 2011-2012 project timeline has made significant advances from the previous design. Off the 19 requirements set and agreed up during the 2011 semester, 6 of the requirement have been fully met, and advances have been made towards most of the other requirements. The team was able to fabricate the new fiberglass strips design, buy and size a new external skin, and write and test an original software code to run the peristaltic motion. The program written during the 2012 spring semester allowed the SERPENTS to move the actuators of each segments at a respectable pace and move each segment in tandem with the other segments. The program was able to achieve the peristaltic motion that the project was initially created to emulate.

9.2 Design Uncertainties (Mallory Brown)

The SERPENTS that was designed, fabricated, and tested during the 2011-2012 project timeline still has a few uncertainties with regard to the design. While testing on the strips was done to determine the load that the fiberglass could take, there is still some uncertainty if the design could function in the service environment. There was some concern by the team that the exerted by the weight of the regolith could collapse the strips inward instead of being bowed outward. Further testing would need to be done in some type of test best to determine if the SERPENTS could operate.

Another uncertainty with regard to the design has to do with the external skin. While abrasion testing was done using the simulant as a type of sandpaper over a small sample of skin, no testing was done where the SERPENTS moved through the material. The skin may not hold up to the combined abrasive surface that the service environment may present.

There is also some uncertainty as to if the SERPENTS could withstand multiple missions. The actuators have held up very well over multiple tests this semester, built has never been determined if the SERPENTS could ascend back up the tunnel using only the peristaltic motion. If the SERPENTS cannot, then it will not survive multiple missions.

9.3 Recommendations (Nathan Wiseheart)

Future recommendations include testing different composite slits to find which will actually pass the load test of about 60 Newton of force. The current fiberglass strips that are being used failed the 60 Newton test. Therefore, this proves that the current design of the strips will not work and they are not sufficient for the SERPENTS's functions. Secondly, the SERPENTS has a tendency to torque or rotate about the axis running the length of the robot. This is due to the type of connections the actuators are connected to the bulkheads with. Therefore, the type of brackets should be evaluated and checked to see if there is another alternative to how the actuators attach to the bulkheads. Finally, the last recommendation is to extend the length of the wiring for connecting the SERPENTS to the LAC controllers. The length was not something that was considered by this team. The purpose of this team was to get the SERPENTS running steadily and reliably. This did not include making sure the wiring harness had enough length for a full blown test in Lunar Simulant. Since this was overlooked, it would be the next semester's team's best interest to look into extending these wires so that a full blown test can be done.

10. Acknowledgements (Mallory Brown)

The 2011-2012 SEPRENTS Team will like to thank the following groups and individuals for their support and assistance given this semester.

Dr. Christina Carmen, MAE 491/492 Instructor
Mr. Blaze Sanders, Customer Representative for NASA
Mr. Joshua Johnson and Mr. Charles Boyles, 2010-2011 Lunar Wormbot Team
Dr. Carson and staff, Video Conference Technical Support
Louisiana Tech University's 2011-2012 SERPENTS Team
The National Space Science and Technology Center (NSSTC)
UAHuntsville Mechanical and Aerospace Engineering Department
UAHuntsville Office of the Vice President of Research
UAHuntsville Dean of the College of Engineering
Alabama Space Grant Consortium
Dr. Wessels and his staff of the Reliability and Failure Analysis Laboratory
UAHuntsville Honors Program

11. References (Mallory Brown)

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12. Appendix A: IAC Abstract and Acceptance Letter

Development of a Novel Peristaltic Motion Robot Designed to Burrow Within Lunar and Martian Regolith

Mallory K. Brown
Mechanical and Aerospace Engineering Department
University of Alabama in Huntsville
Huntsville, Alabama, USA

Christina L. Carmen, Ph.D.
Mechanical and Aerospace Engineering Department
University of Alabama in Huntsville
Huntsville, Alabama, USA

Blaze Sanders
Electrical Engineering Department
Johns Hopkins University
Baltimore, Maryland, USA

ABSTRACT

Collection of lunar regolith was a critical aspect of the National Aeronautics and Space Administration (NASA) Apollo space program. From 1969 to 1972, NASA collected samples of lunar regolith on six different missions; thus enabling geologists to determine the mineral composition of the moon and how the lunar surface was impacted by extraterrestrial events. However, the maximum depth retrieval that the Apollo astronauts achieved was limited to three meters due to the logistical difficulty of the task. In order to broaden the understanding of lunar and other planetary regolith, future space missions will require a tool capable of coring to unexplored depths via an automatic device capable of collecting soil samples from varying depths. The **SE**gmented **R**obotic **P**latform for **E**xploration, se**N**sor **T**ransport and **S**ampling (SERPENTS) project was initiated in order to design a robotic device intended to collect regolith samples from deeper depths than had been previously achieved. The project originated with a NASA Robotics Academy design team at Marshall Space Flight Center (MSFC) in 2010. The team worked with the National Space Science and Technology Center (NSSTC) on the SERPENTS conceptual design before the project was transferred to the University of Alabama in Huntsville (UAH) and Louisiana Tech (LA Tech) in August 2010 for further design refinement, fabrication, and testing. The UAH design team was charged with the task of replicating the peristaltic motion of an earthworm to propel the body of the SERPENTS robot through various regolith depths. The design, fabrication, and testing of the SERPENTS robot by the UAH team was completed utilizing NASA Systems Engineering (SE) design processes. The UAH SERPENTS design team completed extensive technical analysis associated with the structural load conditions, material stresses, and deflections. The UAH team also completed extensive verification tests including cyclic and bending compression tests in conjunction with the UAH Reliability and Failure Analysis Laboratory. The ultimate goal for the system is to become an

instrumental platform, specifically in the scientific exploration of Mars and the moon, though applicable to other planetary bodies-including the Earth. The ability to return scientific samples at various depths, make in-situ measurements, or act as a sensor deployment system will open the door to previously unexplored scientific regions. The present paper will provide an overview of the SERPENTS project, with an emphasis on the UAH design, fabrication, and testing of the SERPENTS body segments.

INTERNATIONAL ASTRONAUTICAL FEDERATION

17 April 2012

Ms. Mallory Brown
University of Alabama in Huntsville
Richmond, KY, United States

63rd International Astronautical Congress
Naples, Italy - 1 – 5 October 2012

Subject: IAC 2011 – Notification to Authors

Dear Ms. Brown,

As Co-Chairs of the IAF International Programme Committee, we first would like to thank you for submitting an abstract for the 63rd International Astronautical Congress. As for the past few years, the response to the Call for Papers has exceeded our expectations and we reached this year an historical record with almost 3,200 submissions online. There were a large number of excellent abstracts to review making the selection quite difficult for the International Programme Committee during the annual IAF Spring Meetings, which took place last March in Paris.

Due to this very high number of abstracts and considering the interest of the subject you proposed, the Committee decided to promote your abstract **"Development of a Novel Peristaltic Motion Robot Designed to Burrow Within Lunar and Martian Regolith"** to a **poster presentation**. It will allow you a high visibility with the audience. Indeed, the Poster Area will occupy a large area in the Naples Congress Center. Posters will remain accessible to all Congress participants from Monday 10:00 to Friday 17:00 and the Congress programme will clearly specify that poster presentations will run every day during the lunch breaks. In addition, a social event will be organized during the week, inviting all the Congress participants to meet in the Poster Area. Finally, note that you could provide a full length paper corresponding to your poster to the IAF Secretariat and it will be included in the congress proceedings just as the oral presentation papers.

Please find the details of your poster hereunder:

Symposium	A3. SPACE EXPLORATION SYMPOSIUM
Session	2D. Moon Exploration – Poster session
Paper ID Nr.:	IAC-12, A3,2D,11,x14259

The exact location of the poster session and the instructions to prepare your poster will be communicated to you **mid-May** with the contact details of your session chairs.

IAF Secretariat - 94bis avenue de Suffren - 75015 Paris, France
T: +33 (0)1 45 67 42 60 - F: +33 (0)1 42 73 21 20 - E: info@iafastro.org - W: www.iafastro.org
Non-profit organisation established under the French Law of 1 July 1901

INTERNATIONAL ASTRONAUTICAL FEDERATION

We would like to ask you to confirm your attendance and presentation to the IAF Secretariat (support@iafastro.org) and session Chairs by **15 June 2012**, and to inform your co-author(s) that the above mentioned abstract has been accepted.

Online registration will be available shortly (www.iac2012.org) and Early bird fees will be valid **until 1st August 2012**. Please note that the publication of the papers in the Congress proceedings will only be possible if the registration fee is paid by at least one the authors and if the paper is uploaded on the IAF website before 12 September 2012.

Do not hesitate to contact the IAF Secretariat (support@iafastro.org) should you have any questions on the technical programme.

We look forward to seeing you in Naples!

Yours Sincerely,

Antonio Moccia

Antonio Moccia
IPC Co-Chair

Li Ming
IPC Co-Chair

Michel Arnaud
Advisor to the IPC Co-Chair

13. Appendix B: Concept Design Document

Concept Description Document
SERPENTS Project
Prepared by
MAE 490-02 Team 3 Project Office
The University of Alabama in Huntsville
Huntsville, AL

Customer Representative:
Blaze Sanders
NASA
Phone: (202) 657-6569
Email: blaze.sanders@solarsystemexpress.com

This Concept Description Document 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.

NOTE : ALL REQUIREMENTS MUST BE 'SHALL' STATEMENTS

Concept Description Document Approval

The undersigned agree that the attached Concept Description Document as marked will be the basis for or MAE 490 Class Project. From this time forward, any questions or clarifications concerning the Concept Description Document shall be submitted in writing through the MAE 490 Instructor to the Customer Representative and the answer distributed to all MAE 490 participants in writing.

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

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

____________________________/________________

Blaze Sanders, Customer Representative

____________________________/________________

Mallory Brown, Student, mkb1081@uah.edu

____________________________/________________

Michael Pinkston, Student, mcp0003@uah.edu

____________________________/________________

Johnny Dingler, Student, johnny.w.dingler@ulalaunch.com

____________________________/________________

Nathan Wiseheart, Student, naw0004@uah.edu

____________________________/________________

Randy Brackins, Student, rdb0004@uah.edu

____________________________/________________

Christina Carmen, MAE 490 Instructor

1. SCOPE

This specification establishes the requirements for the SERPENTS Project. The mission of the SERPENTS Project is to design a prototype that will burrow into the lunar regolith in order to collect soil samples. The SERPENT shall achieve this through the use of the peristaltic motion of the body segments, a conical auger, and an ultrasonic drill head.

2. REQUIREMENTS

2.1 System description.

The SERPENT is described in terms of its physical and functional relationship to other systems required to perform the intended mission.

2.1.1 Physical description. The SERPENT shall consist of the auger and ultrasonic drill at the front of the device creating the head section. The head section shall be followed by 8 body segments that are 200 mm in length (maximum) that will contract down to 100 mm in length. The current body length of the SERPENT shall be 1600 mm in length.

2.1.2 Functional description. The SEPRENT is a robotic tool used to acquire soil samples from varying depths in the lunar regolith. The SERPENT shall function by burrowing into the lunar regolith using an ultrasonic drill bit and conical auger in the head section, and peristaltic motion in the trailing body segments.

2.1.3 Mission Statement: To develop knowledge in order to enable a robot to operate on the lunar regolith in order to obtain soil samples from varying depths. The SERPENT shall be capable of burrowing through fine particulate soil simulant to a fixed depth, and return to the surface with collected data and samples. A prototype of the robot, to be produced during the project timeline, is to be designed for Earth-based testing. The goal of the UAH Team is to design and fabricate the body segments that shall be capable of moving using peristaltic motion.

2.2 Major component list.

The SERPENT will consist of three main subsystems,two of which will be the responsbiliy of the UAH and LA Tech desgin teams. The three main subsystesm are the head section, the combined eight body segments, and the above ground support system. The support system will be developed separate from the rest of the SERPENT after the rest of the SERPENT has been further developed.

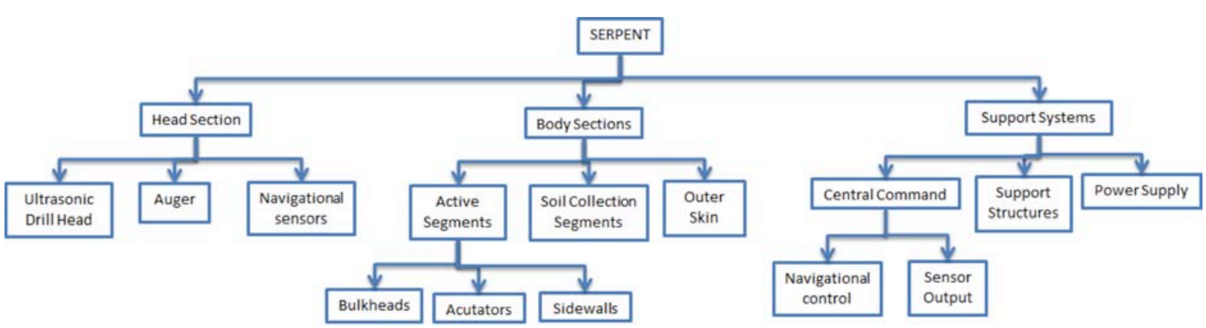

Figure 1 – Major Component Diagram

2.2.1. **Head Section**: The head section is located at the furthest front section of the SERPENT. The head section is further separated in to three broad components. The head section shall be designed and constructed by the LA Tech team.

2.2.1.1. Ultrasonic Drill Bit: The ultrasonic drill bit is located at the very leading edge of the SERPENT. The drill bit shall be capable of breaking up larger matter in the lunar regolith.

2.2.1.2. Auger: The auger is located right behind the ultrasonic drill bit. The auger shall be conical in shape and capable of moving the lunar regolith out the path of the SERPENT. The auger shall be propelled by a motor located in the head section.

2.2.1.3. Navigation / Sensory Component: The head section shall contain a package of navigational sensors capable of detecting larger rocks in the pathway of the SEPRENT as it descends.

2.2.2. **Body Sections**: The body segments are located directly behind the head section. The body section will consist of three main components: the active segments, the soil collection segments, and the outer protective skin.

2.2.2.1. Active Segments: The active segments shall be the segments that propel that SERPENT forward using peristaltic motion through the application of force perpendicular to the SERPENT's line of action. The active segments are comprised of three subcomponents: the linear actuators, the bulkheads, and the sidewalls. The active segments shall be designed and constructed by the UAH team.

2.2.2.1.1. Linear Actuators: The peristaltic motion of the SEPRENT shall be achieved using linear actuators to compress and distend the active segments. The linear actuators shall exert 66N of force upon the walls of the burrowed tunnel (as specified by NASA engineers to the previous team).

2.2.2.1.2. Bulkheads: Each individual body segment will be conjoined to the next body segment through the use of solid metal bulkheads. The head section will also be joined to the body section (as a whole) by the use of a bulkhead. The bulkhead of the head section shall be bolted to the forward most bulkhead of the body section. Each individual body segment shall be joined to each other through identical bulkheads. The diameter of the bulkheads shall be 152.4mm (6in).

2.2.2.1.3. Sidewalls: The sidewalls of each individual body section shall extend outward perpendicular to the SERPENT's line of action. This is to allow the linear actuators to compress each segment in order to create the peristaltic motion.

2.2.2.1.4. Brackets: Each linear actuator is attached to the bulkhead with metal brackets that will compensate for multiple dimensions of movement of the actuators. If one actuator extends further than the others, the brackets will allow for that movement without doing damage to the actuator.

2.2.2.2. Soil Collection Segments: The body section shall incorporate segments whose purpose is to collect one-gram samples every specific interval. The soil collection segments shall be handled by LA Tech.

2.2.2.3. Outer Skin: Each individual body segment shall be enclosed by a touch, water-tight skin that will protect the internal electrical and mechanical components. The outer skin shall be designed and constructed by the UAH team as a part of the active body segments.

2.2.3. **Support System**: The SERPENT shall have an above ground support system that will provide power, navigation, and external support to the SERPENT will in operation. The support system halls include a grounded support structure to provide a sturdy attachment to the SERPENT. The support structure could also be used in retrieving the SERPENT in case of failure. The support system shall be the responsibility of a future UAH or LA Tech team. The programing of the SERPENT shall be the responsibility of the UAH team with assistance from Mr. Blaze Sanders.

2.3 Performance Characteristics.

These can include items such as speed, range, time of operations, pressure levels, operational environments, etc.

2.3.1. Requirement 1. The SERPENT shall be capable of burrowing through fine particulate matter. (UAH Team)

2.3.2. Requirement 2. The SERPENT shall implement peristaltic locomotion to allow one-dimensional burrowing. It should have segments articulated in three dimensions. (UAH Team)

2.3.3. Requirement 3. The SERPENT shall be designed for Earth-based testing. (UAH Team, LA Tech Team)

2.3.4. Requirement 4. The SERPENT shall take 50 one-gram samples at a specific interval over the 15m burrowing depth (LA Tech Team).

2.3.5. Requirement 5. The SERPENT shall utilize a power supply of 5 W or less (UAH Team).

2.3.6. Requirement 6. The SERPENT's head section shall be made up of an ultrasonic drill bit and a conical auger (LA Tech Team).

2.3.7. Requirement 7. The SERPENT shall utilize an elastic water-tight skin to protect the interior electrical and mechanical systems from the fine particulate matter (UAH Team).

2.3.8. Requirement 8. The SERPENT shall incorporate the space to include a navigational and sensory package (UAH Team, LA Tech Team).

2.3.9. Requirement 9. The SERPENT shall be capable of returning to the surface to deliver the soil samples (UAH Team).

2.3.10. Requirement 10. The SEPRENT shall be capable to survive multiple missions of burrowing 15 m then ascending back to the surface (UAH Team).

2.3.11. Requirement 11. The SERPENT should apply mechanical force by means of motors or actuators situated perpendicular to its longitudinal axis (UAH Team).

2.3.12. Requirement 12. The SERPENT shall be analyzed using modeling and simulation techniques prior to prototype testing. (UAH Team)

2.3.13. Requirement 13. The SERPENT auger shall be designed to optimize soil displacement and forward motion (LA Tech Team).

2.3.14. Requirement 14. Individual dummy segments shall be between 50% and 90% of locomotion segment volume (LA Tech Team).

2.3.15. Requirement 15. The SERPENT shall produce at least 66 N of force directed perpendicular to the segment's longitudinal axis at the center hinge (UAH Team).

2.3.16. Requirement 16. The SERPENT shall be designed to withstand temperature extremes on the lunar surface (UAH Team, LA Tech Team).

2.3.17. Requirement 17. The SERPENT shall be provided with electrical power through the use of a cable extended from the surface (UAH Team).

2.3.18. Requirement 18. The SERPENT shall be tested at the KSC test bed in May 2012 (UAH Team).

2.3.19. Requirement 19. The brackets attaching the linear actuators to the bulkhead will allow for 3 dimensional movements (UAH Team).

2.4 Operational Characteristics.

2.4.1 Facilities, transportation, and storage. The SERPENT shall be manufactured at the NSSTC machine shop.

2.4.2 Installation/Removal. The SERPENT shall have an apparatus to position, initial, and extract the SERPENT from the lunar regolith.

2.4.3 Reliability. The SERPENT shall be capable to making multiple trips to a depth of 15 m and return to the surface.

2.4.4 Mission Reliability. The SERPENT shall run on power provided by the support structure, thus the reliability of the system breaking is greater than if the SERPENT carried its own independent power supply without above ground support.

2.4.5 Storage Reliability. The SERPENT shall be capable of being stored for up to 3 years without failure. The SERPENT shall be stored in a room temperature, no-humidity room. This shall prevent deterioration of the SERPENT over time.

2.4.6 Safety. The SERPENT has a significant mass and hazardous pinch points between the moving metal sections, therefore the SERPENT is not to be in operation during transportation. In order to avoid bodily injury from metal joints, personal should avoid those areas during operation. Also, due to the SERPENT utilizing electrical power, whenever maintenance is to be done, all power is to be cut to the SERPENT to avoid accidents.

2.4.7 Mechanical Safety/Hazardous Materials. The largest safety concern in regards to the SERPENT are the metal pinch points between the actuators or motors, therefore all personal should avoid contact with the SERPENT will it is in motion.

2.4.8 Drop Safety. Due to the significant size and weight of the SERPENT, and the SERPENT's cylindrical shape, foot protection is advised whenever around SERPENT. Structural and outer skin integrity could be compromised if dropped from a significant height.

2.4.9 Human Performance/Human Engineering. The human engineering of the SERPENT shall be minimal. The human interaction shall be limited to maintenance (i.e. skin repair and actuator maintenance), the operation (navigation and running of sensory programs), and removal of collected soil samples.

2.4.10 Personnel. The personnel needed for the operation and support of the SERPENT should be minimal due to the SERPENT's semi-autonomous operation. The personnel will include a small team to operate the SERPENT on the lunar surface, and a small to medium team to service all useable SERPENTS.

2.4.11 Training. Due to the semi-autonomous design of the SERPENT, training will be minimal. Personnel will be trained in navigation of the SERPENT and initial set-up, but the SERPENT will be capable of burrowing unaided. There will be some training in order for a technician to navigate the SERPENT based on the sensory data sent from the SERPENT. There will also be a short training program on how to remove the soil samples once the mission is complete. There will more extensive training for the repair technicians to service the SERPENT.

2.4.12 Maintenance. The SERPENT's outer skin should be cleaned, inspected, and repaired after a specified number of missions. Also as needed, the internal mechanical and electrical systems should be replaced.

3.0 CLARIFICATIONS AND GUIDELINES

3.1. Blaze Sanders, Customer Representative

3.1.1. Question: Are the previously decided upon requirements still valid? Answer: Yes

3.1.1. Question: Is the Wormbot designed to be single or multiple use? Answer: SERPENTS is being design to survive 7 mission (1 mission = down and up) to a depth of 15 m

3.1.2. Question: What is the power source of the Wormbot? Answer: Power source is a surface station, connect to SERPENTS by tether.

3.1.3. Question: Is there a target size and weight? Answer: Target size is hard to define, it depends on actuator size and power density. This is an important idea to research and optimize. But a segment size of smaller than 200 mm long x 100 mm diameter is a goal.

3.1.4. Question: How much human interaction will the Wormbot have? Answer: None while drilling down, possibly semi-autonomous when it's on the surface.

3.1.5. Question: Do the design criteria from the previous semester still stand? If not, what changes? Answer: Yes it still stands expect for power requirement. System should aim for less than 5 W of instantaneous power

3.1.6. Question: Will SERPENTS be autonomous going up, or will human interaction be required at this stage? Answer: It will be semi-autonomous going up as well. Above surface navigation; however, will involve near complete human control. For this early prototype at least.

3.2. Joshua Johnson, Past Lunar Wormbot Team Member

3.2.1. Question: Looking back what changes would you have made to the Wormbot? Answer: The skin would have been designed differently. The segments would also have been smaller.

3.2.2. Question: Did you research anything besides the carbon fiber stripes? Answer: We looked into some spring steel before deciding on the carbon fiber.

3.2.3. Question: What was the biggest problem the team had last year? Answer; parts procurement. We ordered the parts in November for fabrication in February, and they didn't arrive until the middle of April.

3.2.4. What made the team decide to go with the leather skin? Answer: The skin was to be designed by the CE department. The wormbot ended up with the leather at the end because it wasn't a part of our project.

4.0 REVISIONS

1) CCD_1 (original)
2) CCD_2
3) CDD_3

5.0 GLOSSARY

This glossary defines every acronym in the document.

UAH –University of Alabama in Huntsville
KSC – Kennedy Space Center
LA Tech – Louisiana Tech University

5.0 REFERENCES

2010-2011 MAE490 Lunar Wormbot Team. "Lunar Wormbot." 2011 ESMD Systems Engineering Paper Competition submission. 2011.

14. Appendix C: Product Design Specification

Product Design Specification
SERPENTS Project
Prepared by
MAE 490 Team 3 Project Office
The University of Alabama in Huntsville
Huntsville, AL

Customer Representative:
Blaze Sanders
NASA
Phone: (202) 657-6569
Email: blaze.sanders@solarsystemexpress.com

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.

Product Design Specification Approval

The undersigned agree that the attached Product Design Specification as marked describes the product/prototype specifications for the MAE 490 Class Project. From this time forward, any questions, clarifications or changes concerning the Product Design Specification shall be submitted in writing through the MAE 490 Instructor to the Customer Representative and the answer distributed to all MAE 490 participants in writing.

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

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

___________________________/_______________

Blaze Sanders, Customer Representative

___________________________/_______________

Mallory Brown, Student, mkb1081@uah.edu

___________________________/_______________

Michael Pinkston, Student, mcp0003@uah.edu

___________________________/_______________

Christina Carmen, MAE 490 Instructor

1. SCOPE This specification establishes the purpose, functional requirements, corporate constraints and social, political and legal requirements for the SERPENT Project. The mission of the SERPENTS Project is to design a prototype that will burrow into the lunar regolith in order to collect soil samples. The SERPENT shall achieve this through the use of the peristaltic motion of the body segments, a conical auger, and an ultrasonic drill head.

2. CUSTOMER AND MARKET SURVEY REQUIREMENTS The SERPENT is described in terms of its initial requirements and constraints as dictated by the customer survey requirements (CR).

2.1. Requirement 1. The SERPENT shall be capable of burrowing through fine particulate matter. (UAH Team)

2.2. Requirement 2. The SERPENT shall implement peristaltic locomotion to allow one-dimensional burrowing. It should have segments articulated in three dimensions. (UAH Team)

2.3. Requirement 3. The SERPENT shall be designed for Earth-based testing. (UAH Team, LA Tech Team)

2.4. Requirement 4. The SERPENT shall take 50 one-gram samples at a specific interval over the 15m burrowing depth (LA Tech Team).

2.5. Requirement 5. The SERPENT shall utilize a power supply of 5 W or less (UAH Team).

2.6. Requirement 6. The SERPENT's head section shall be made up of an ultrasonic drill bit and a conical auger (LA Tech Team).

2.7. Requirement 7. The SERPENT shall utilize an elastic water-tight skin to protect the interior electrical and mechanical systems from the fine particulate matter (UAH Team).

2.8. Requirement 8. The SERPENT shall incorporate the space to include a navigational and sensory package (UAH Team, LA Tech Team).

2.9. Requirement 9. The SERPENT shall be capable of returning to the surface to deliver the soil samples (UAH Team).

2.10. Requirement 10. The SEPRENT shall be capable to survive multiple missions of burrowing 15 m then ascending back to the surface (UAH Team).

2.11. Requirement 11. The SERPENT should apply mechanical force by means of motors or actuators situated perpendicular to its longitudinal axis (UAH Team).

2.12. Requirement 12. The SERPENT shall be analyzed using modeling and simulation techniques prior to prototype testing. (UAH Team)

2.13. Requirement 13. The SERPENT auger shall be designed to optimize soil displacement and forward motion (LA Tech Team).

2.14. Requirement 14. Individual dummy segments shall be between 50% and 90% of locomotion segment volume (LA Tech Team).

2.15. Requirement 15. The SERPENT shall produce at least 66 N of force directed perpendicular to the segment's longitudinal axis at the center hinge (UAH Team).

2.16. Requirement 16. The SERPENT shall be designed to withstand temperature extremes on the lunar surface (UAH Team, LA Tech Team).

2.17. Requirement 17. The SERPENT shall be provided with electrical power through the use of a cable extended from the surface (UAH Team).

2.18. Requirement 18. The SERPENT shall be tested at the KSC test bed in May 2012 (UAH Team).

3. MAJOR COMPONENT LIST

The SERPENT will consist of three main subsystems,two of which will be the responsbiliy of the UAH and LA Tech desgin teams. The three main subsystesm are the head section, the combined eight body segments, and the above ground support system. The support system will be developed separate from the rest of the SERPENT after the rest of the SERPENT has been further developed.

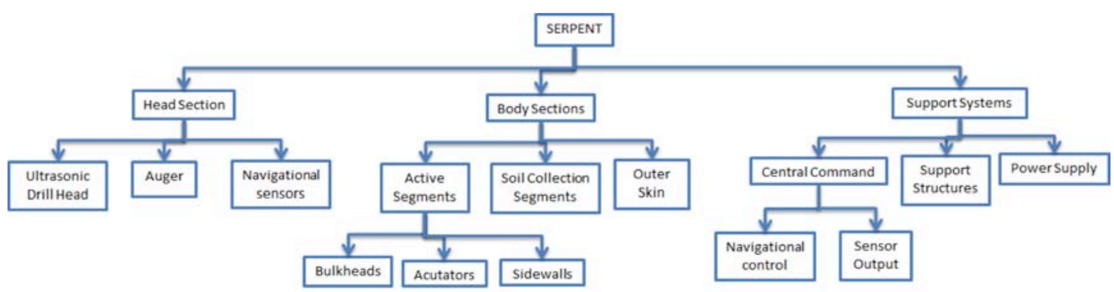

Figure 1 – Major Component Diagram

3.1. **Head Section**: The head section is located at the furthest front section of the SERPENT. The head section is further separated in to three broad components. The head section shall be designed and constructed by the LA Tech team.

3.1.1. Ultrasonic Drill Bit: The ultrasonic drill bit is located at the very leading edge of the SERPENT. The drill bit shall be capable of breaking up larger matter in the lunar regolith.

3.1.2. Auger: The auger is located right behind the ultrasonic drill bit. The auger shall be conical in shape and capable of moving the lunar regolith out the path of the SERPENT. The auger shall be propelled by a motor located in the head section.

3.1.3. Navigation / Sensory Component: The head section shall contain a package of navigational sensors capable of detecting larger rocks in the pathway of the SERPENT it descends.

3.2. **Body Sections**: The body segments are located directly behind the head section. The body section will consist of three main components: the active segments, the soil collection segments, and the outer protective skin.

3.2.1. Active Segments: The active segments shall be the segments that propel that SERPENT forward using peristaltic motion through the application of force perpendicular to the SERPENT's line of action. The active segments are comprised of three subcomponents: the linear actuators, the bulkheads, and the sidewalls. The active segments shall be designed and constructed by the UAH team.

3.2.1.1. Linear Actuators: The peristaltic motion of the SEPRENT shall be achieved using linear actuators to compress and distend the active segments. The linear actuators shall exert 66N of force upon the walls of the burrowed tunnel (as specified by NASA engineers to the previous team).

3.2.1.2. Bulkheads: Each individual body segment will be conjoined to the next body segment through the use of solid metal bulkheads. The head section will also be joined to the body section (as a whole) by the use of a bulkhead. The bulkhead of the head section shall be bolted to the forward most bulkhead of the body section. Each individual body segment shall be joined to each other through identical bulkheads. The diameter of the bulkheads shall be 152.4mm (6in).

3.2.1.3. Sidewalls: The sidewalls of each individual body section shall extend outward perpendicular to the SERPENT's line of action. This is to allow the linear actuators to compress each segment in order to create the peristaltic motion.

3.2.2. Soil Collection Segments: The body section shall incorporate segments whose purpose is to collect one-gram samples every specific interval. The soil collection segments shall be handled by LA Tech.

3.2.3. Outer Skin: Each individual body segment shall be enclosed by a touch, water-tight skin that will protect the internal electrical and mechanical components. The outer skin shall be designed and constructed by the UAH team as a part of the active body segments.

3.3 **Support System**: The SERPENT shall have an above ground support system that will provide power, navigation, and external support to the SERPENT will in operation. The support system halls include a grounded support structure to provide a sturdy attachment to the SERPENT. The support structure could also be used in retrieving the SERPENT in case of failure. The support system shall be the responsibility of a future UAH or LA Tech team. The programing of the SERPENT shall be the responsibility of the UAH team with assistance from Mr. Blaze Sanders.

4. PURPOSE AND MARKET FOR PRODUCT

4.1 Product Name: SEPRENT

4.2 Product Purpose and Function it is to Perform: The SERPENT's purpose is to collect soil samples from a prescribed depth of 15m through the use of an ultrasonic drill bit, conical auger, and peristaltic motion of the trailing body segments. The SERPENT is deployed, and then burrow in to the ground through the combined head and body segments while simultaneously taking one-gram samples from the surround soil. The SERPENT will then return to the surface through the use of the body segments and support structure.

4.3 Predictable Unintended Uses of Product:

4.3.1. Scientific Applications: soil sampling for Earth testing, planetary exploration

4.3.2. Military Applications: hidden explosive detection, intelligence gathering, post-crisis rescue operations

4.3.3. Commercial Applications: mining / pre-mining soil samples, telecommunications, groundwater and water table sampling,

4.4 Product Special Features:

4.4.1: Drill Feature: Conical Auger with Ultrasonic drill bit

4.4.2. Peristaltic Motion Feature: Mechanical body segments, and system programming

4.4.3. Soil Sample Collectors: to be designed

4.5 Intended Market, Need, Demand:

4.5.1. Intended Market: NASA / NSSTC

4.5.2. Market Need: One prototype

4.5.3: Market Demand: There is no market demand past the one prototype.

4.6 Company Selling Price/Estimated Retail Price: To be estimated once product is past prototype stage.

4.7 Product Competition: convention mining systems

5. FUNCTIONAL REQUIREMENTS

5.1 Functional Performance:

5.1.1 Flow of Energy: The SERPENT body segments will not have independent power supplies. All power will flow from the support structure (above ground) to the SERPENT segments through an electrical tether.

5.1.2. Flow of Information: all operational control will come from the central controller that is part of the support structure. A human operator will control the SERPENT from above ground. The instructions flow down the tether to the master-slave Arduino board system.

5.1.3. Material Performance: The SERPENT shall be able to withstand axial force (from the head section's conical auger) and transverse force (from the body segments' peristaltic motion).

5.1.4. Operational Steps: The operation of the SERPENT proceeds in the following manner. The SERPENT is positioned in its starting position through the use of the structural above ground supports. The SERPENT's linear actuators and conical auger are brought online. While inactive, these segments are locked to prevent unnecessary damage to components or risks to operators. The central control unit begins the drilling program (for the ultrasonic drill bit and conical auger). Once the body segments have entered the soil, the central controller sends a command to the body segments' Arduino boards to being the peristaltic motion program. The program will instruct the linear actuators in alternating segments to contract or extend creating a transverse force upon the thin walls of the burrowed tunnel. The SERPENT shall proceed to a depth of 15 meters with both programs running. Once the SERPENT reaches the required depth, the central controller will send a set of instructions to the linear actuators to reverse their motion and a program to the head section to stop work. The SERPENT shall then return to the surface with the collected soil samples.

5.1.5. Functional Efficiency: to be determined during testing

5.1.6. Functional Accuracy: to be determined during testing

5.2 Physical Requirements:

5.2.1. Size: An individual body segment is 6 inches in diameter and 7.9 inches in length when extended. The body segment constricts to 4 inches in length. Overall, the SERPENT body section shall have eight body segments for a full (extended length) of approximately 80 inches.

5.2.2. Weight: Each individual body segment weights between 2 - 4 pounds, leading to a full body weight (minus head section) of 16 – 32 pounds.

5.2.3. Materials: The bulkheads will be composed of aluminum alloy with the force stripes being composed of carbon fiber.

5.2.4. Protective Skin: The outer protective skin will be composed of either a leather material or a donated space raced protective material.

5.2.5. Programing: The SEPRENT shall be controlled through a master-slave Arduino board system. All commands will come from the central control station (part of the support structure) that is located above ground. The peristaltic motion will be autonomous, but direction and sensory input will be operator controlled.

5.3 Service Environment: The SERPENT is designed to work in a lunar regolith simulant material. The simulant closely resembles the fine particular matter found on the lunar surface.

5.4 Life-Cycle Issues:

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

5.4.2. Failure: Most failures are due to particulate matter breeching the internal components leading to breakdowns (i.e. breakdown of linear actuators, severance of power lines, tears of carbon fiber stripes).

5.4.3. Maintainability: Due to the segmented design of the SERPENT, parts can be easily serviced or replaced as needed. Also, due to the small number of differing parts, the SERPENT has only a limited number of potential problems. Thus maintenance time and costs are reduced.

5.4.4. Testability: The SERPENT is designed to operate in differing environments to be determined at a later date.

5.4.5. Reparability: The integrity of the skin will determine the level of difficulty in repair and how often repair will be necessary.

5.4.6. Retirement: Due to the majority of components being made of metal, the majority of the SERPENT can be recycled once service has ended. The time at which this point is reached will be determined in testing.

5.4.7. Cost of Operation: cost of operation will be determined based on storage of device, training of personnel, maintenance of components, transportation of device, and availability of parts.

5.5 Human Factors:

5.5.1. Aesthetics: N/A

5.5.2. Ergonomics: N/A

5.5.3. Maintenance: Due to segmented design, components are easy to assess, leading to manageable maintenance.

5.5.4. Operational Training: operators will be trained in handling of the SERPENT, maintenance and emergency repair, and control of the SERPENT.

5.6 Facilities, Transportation and Storage:

5.6.1. Facilities: The manufacturing will be done in a standard machine shop. The head segment (if needed) will have special manufacturing requirements.

5.6.2. Transportation: The SERPENT shall not exceed 85 inches in length, and 34 pounds in weight making it small enough to be transported without specially made equipment. For transportation from one location to another, a car or truck (preferably) will be able to move the SERPENT. For interior moves, two person lift is preferred when lifting the SERPENT to avoid accident drops or unforeseeable injury. Use of a cart is advised when moving the SERPENT indoors.

5.6.3. Storage: The SERPENT shall be stored in an air conditioned (set at standard room temperature) humidity less room while not in use.

6. CORPORATE CONSTRAINTS

6.1 Time to Market: The 2011-2012 SERPENT design was finalized during the fall 2011 semester. The new stripe and skin for the existing SERPENT will be fabricated February – March of the 2012 Spring semester. The SERPENT will be tested during April and final testing at KSC will take place in May 2012.

6.2 **Manufacturing Requirements:** The manufacturing will be done in a standard machine shop. The head segment (if needed) will have special manufacturing requirements.

6.3 **Suppliers:**
6.3.1 Linear Actuators: reuse of previously acquired components
6.3.2 Bulkheads: reuse of previously acquired components
6.3.3. Stripes: onlinemetals.com – readily available
6.3.3 Skin: finalfrontierdesign.com – readily available

6.4 **Trademark, Logo, Brand Name:** no known conflicts

6.5 **Financial Performance:** Based on final testing, the SEPRNT may have commercial demand for the product.

6.6 **Corporate Ethics:** To be determined

6.7 **Budget:** based upon lasted year budget, $6,000.

7. SOCIAL, POLITICAL AND LEGAL REQUIREMENTS

7.1 **Safety and Environmental Regulations:**
7.1.1. Safety Regulations: Manufacturing and mission processes shall be performed in accordance with OSHA standards.
7.1.2. End of Service Life Disposal: The disposal of hazards materials shall be determined based on the local codes of the area where the storage facilities are located.

7.2 **Standards:** to be determined

7.3 **Safety and Product Liability:** Warning labels shall be placed on the SERPENT to avoid accident hazards; this includes the pinch points and electrical hazards near the support structure. Training of all personnel that will interact with the SERPENT will include a large safety requirement.

7.4 **Patents and Intellectual Property:**
7.4.1. Patented Parts: to be determined
7.4.2. Similar Patented Products: There are no similar products at this time.
7.4.3. Intellectual Property: to be determined
7.4.4 Infringement Avoidance: to be determined

8.0 Glossary

This glossary defines every acronym in the document.

PDS – Product Design Specification
CR – Customer Requirement
UAH –University of Alabama in Huntsville
LA Tech – Louisiana Tech University
KSC – Kennedy Space Center

9.0 References

9.1. 2010-2011 MAE490 Lunar Wormbot Team. "Lunar Wormbot." 2011 ESMD Systems Engineering Paper Competition submission. 2011.

9.2. United States. Air Force Safety Center. *Air Force System Safety Handbook*. Kirkland AFB: 2000. Web.

15. Appendix D: Arduino Program

```
/* Use with LAC from Firgelli using PWM*/


int PWM1 = 11;
int switch1 = 13;
int PWM2 = 10;
int switch2 = 12;
int PWM3 = 9;
int switch3 = 8;
int PWM4 = 6;
int switch4 = 7;
int PWM5 = 5;
int switch5 = 4;
int PWM6 = 3;
int switch6 = 2;
int minval = 10;
int maxval = 960;
int value1;
int value2;
int value3;
int value4;
int value5;
int value6;
void setup (){
```

```
  pinMode(switch1,OUTPUT);
  pinMode(switch2,OUTPUT);
  pinMode(switch3,OUTPUT);
  pinMode(switch4,OUTPUT);
  pinMode(switch5,OUTPUT);
  pinMode(switch6,OUTPUT);
  pinMode(PWM1,OUTPUT);
  pinMode(PWM2,OUTPUT);
  pinMode(PWM3,OUTPUT);
  pinMode(PWM4,OUTPUT);
  pinMode(PWM5,OUTPUT);
  pinMode(PWM6,OUTPUT);
  Serial.begin (9600);
}

void loop(){
  delay(3000);
  for (int i = 1; i < 13; i++){
    if (i = 1){
      Serial.print("i = 1" );
      for ( value1 = minval; value1 < maxval; value1++){
        digitalWrite(switch1,HIGH);
        analogWrite(PWM1,(value1)/4);
        Serial.println(value1);
        delay(1);
```

```
    }
    delay(3000);
    digitalWrite(switch1,LOW);
    delay(1000);
  }
if (i = 2){
  Serial.print("i = 2 ");
  for (value2 = minval; value2 < maxval; value2++){
    digitalWrite(switch2,HIGH);
    analogWrite(PWM2,(value2)/4);
    Serial.println(value2);
    delay(1);
  }
  delay(3000);
  digitalWrite(switch2,LOW);
  delay(1000);
}
if (i = 3){
  Serial.print("i = 3");
  for (value3 = minval; value3 < maxval; value3++){
    digitalWrite(switch3,HIGH);
    analogWrite(PWM3,(value3)/4);
    Serial.println(value3);
    delay(10);
  }
```

```
  delay(3000);
  digitalWrite(switch3,LOW);
  delay(1000);
 }
 if (i = 4){
  Serial.print("i = 4");
  for (value4 = minval; value4 < maxval; value4++){
   digitalWrite(switch4,HIGH);
   analogWrite(PWM4,(value4)/4);
   Serial.println(value4);
   delay(1);
  }
  delay(3000);
  digitalWrite(switch4,LOW);
  delay(1000);
 }
 if (i = 5){
  Serial.print("i = 5");
  for (value5 = minval; value5 < maxval; value5++){
   digitalWrite(switch4,HIGH);
   analogWrite(PWM5,(value5)/4);
   Serial.println(value5);
   delay(10);
  }
  delay(3000);
```

```
  digitalWrite(switch5,LOW);
  delay(1000);
 }
 if (i = 6){
  Serial.print("i = 6");
  for (value6 = minval; value6 < maxval; value6++){
   digitalWrite(switch6,HIGH);
   analogWrite(PWM6,(value6)/4);
   Serial.println(value6);
   delay(1);
  }
  delay(3000);
  digitalWrite(switch6,LOW);
  delay(1000);
 }
 delay(1500);
 if (i = 7){
  Serial.println("i = 7");
  for (value6 = maxval; value6 > minval; value6--){
   digitalWrite(switch6,HIGH);
   analogWrite(PWM1,(value6)/4);
   Serial.println(value6);
   delay(1);
  }
  delay(3000);
```

```
  digitalWrite(switch6,LOW);
  delay(1000);
 }
 if (i = 8){
  Serial.print("i = 8");
 for (value5 = maxval; value5 > minval; value5--){
  digitalWrite(switch5,HIGH);
  analogWrite(PWM5,(value5)/4);
  Serial.println(value5);
  delay(1);
 }
 delay(3000);
 digitalWrite(switch5,LOW);
 delay(1000);
 }
 if (i = 9){
  Serial.print("i = 9");
 for (value4 = maxval; value4 > minval; value4--){
  digitalWrite(switch4,HIGH);
  analogWrite(PWM4,(value4)/4);
  Serial.println(value4);
  delay(1);
 }
 delay(3000);
 digitalWrite(switch4,LOW);
```

```
delay(1000);
}
if (i = 10){
  Serial.print("i = 10");
for (value3 = maxval; value3 > minval; value3--){
  digitalWrite(switch3,HIGH);
  analogWrite(PWM3,(value3)/4);
  Serial.println(value3);
  delay(10);
}
delay(3000);
digitalWrite(switch3,LOW);
delay(1000);
}
if (i = 11){
  Serial.print("i = 11");
for (value2 = maxval; value2 > minval; value2--){
  digitalWrite(switch2,HIGH);
  analogWrite(PWM2,(value2)/4);
  Serial.println(value2);
  delay(1);
}
delay(3000);
digitalWrite(switch2,LOW);
delay(1000);
```

```
 }
 if (i = 12){
  Serial.print("i = 12");
 for (value1 = maxval; value1 > minval; value1--){
  digitalWrite(switch1,HIGH);
  analogWrite(PWM1,(value1)/4);
  Serial.println(value1);
  delay(1);
 }
 delay(3000);
 digitalWrite(switch1,LOW);
 delay(1000);
 }
 }
}
```

16. Appendix E: CAD drawings with dimensions (Nathan Wiseheart)

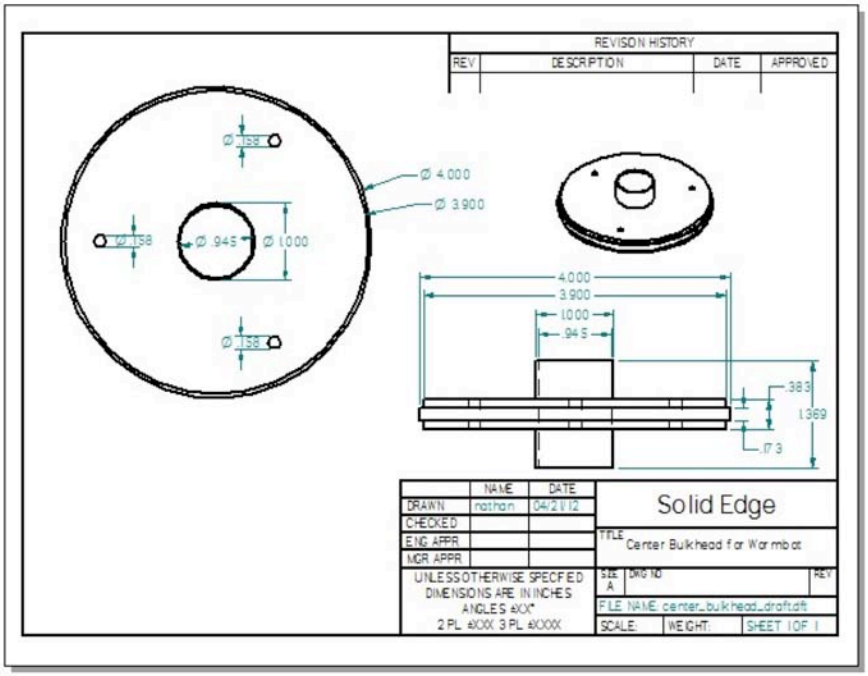

Figure 37: Center Bulkhead

CAD Drawing provided by N. Wiseheart

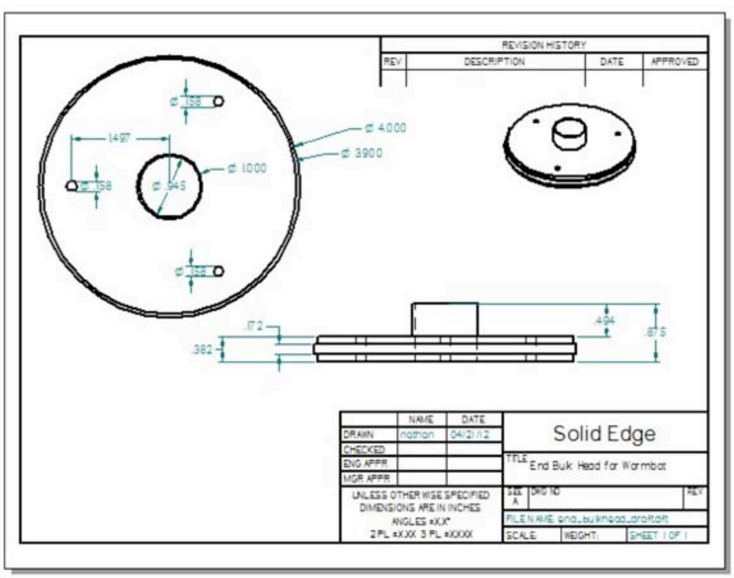

Figure 38: End Bulkhead

CAD Drawing provided by N. Wiseheart

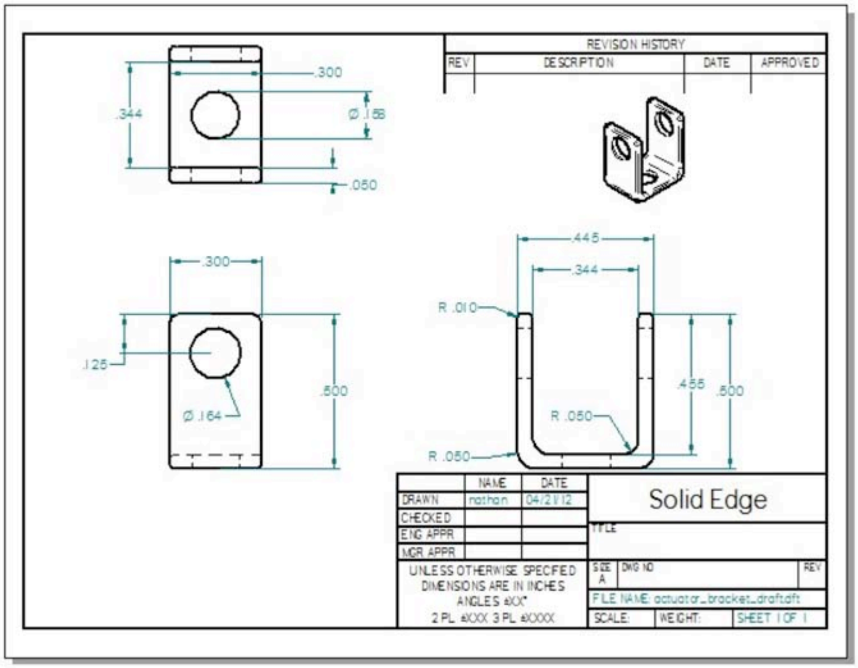

Figure 39: Brackets

CAD Drawing provided by N. Wiseheart

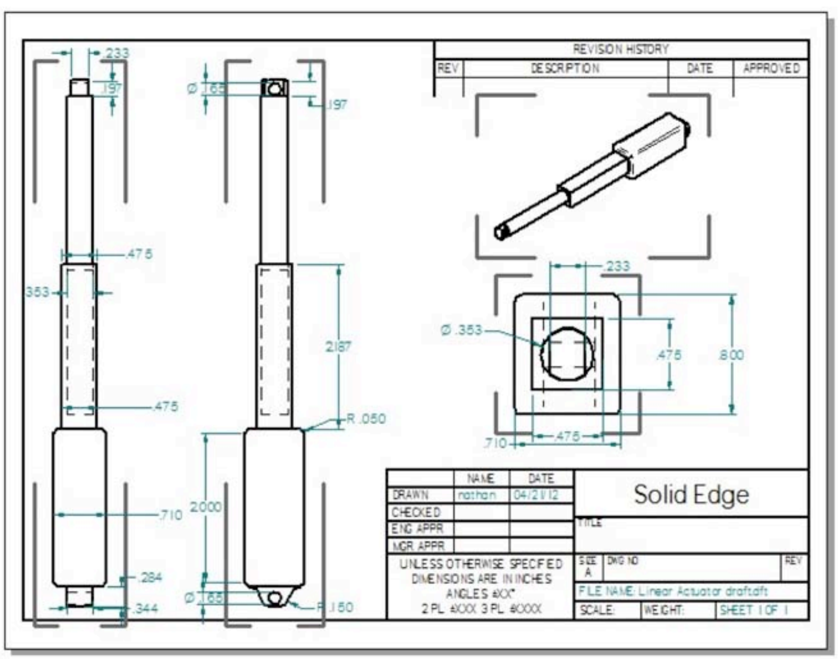

Figure 40: Actuator

CAD Drawing provided by N. Wiseheart

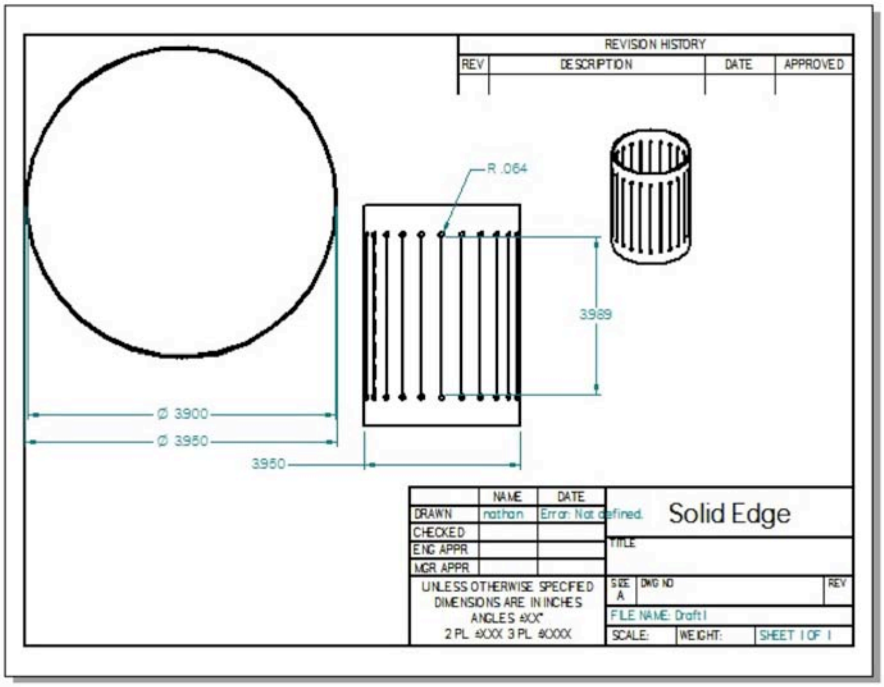

Figure 41: Fiberglass

CAD Drawing provided by N. Wiseheart

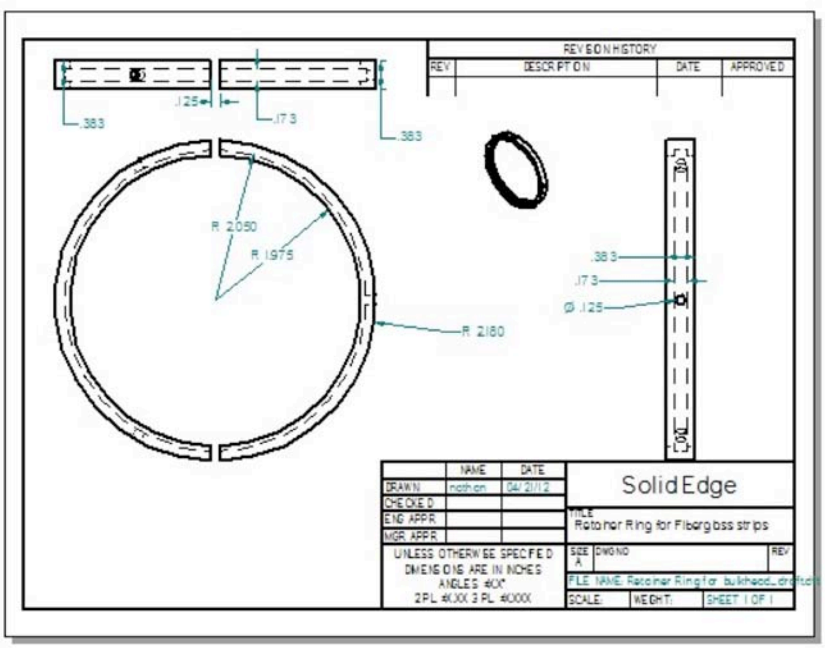

Figure 42: Retainer Ring

CAD Drawing provided by N. Wiseheart

17. Appendix F: Requirements Verification Matrix

Table 6: Requirements Verification Matrix

REQ No.	DOC.	Paragraph	Shall Statement	Verification Success Criteria	Verification Method	Facility or Lab	Performing Organization	Results
1	CDD	2.3.1	The SERPENT shall be capable of burrowing through fine particulate matter.	1. The body linear actuators compress and extend to form the peristaltic motion. 2. The skin does not break down after extended filings using the soil simulant.	1. linear actuator test 2. skin abrasion test 3. full systems test	UAH	UAH Team	not met
2	CDD	2.3.2	The SERPENT shall implement peristaltic locomotion to allow one-dimensional burrowing. It should have segments articulated in three dimensions.	The body linear actuators compress and extend to form the peristaltic motion	linear actuator test	UAH	UAH Team	Met
3	CDD	2.3.3	The SERPENT shall be designed for Earth-based testing.	The skin does not break down after extended filings using the soil simulant.	skin abrasion test	UAH, other	UAH Team, LA Tech Team	Met
4	CDD	2.3.4	The SERPENT shall take 50 one-gram samples at a specific interval over the 15m burrowing depth	this requirement is under the jurisdiction of the LA Tech Team and will be verified by them.		other	LA Tech Team	not met
5	CDD	2.3.5	The SERPENT shall utilize a power supply of 5 W or less	The body linear actuators compress and extend to form the peristaltic motion	1. linear actuator test 2. full systems test	UAH	UAH Team	Met

Table 6: Requirements Verification Matrix (continued)

REQ No.	DOC.	Paragraph	Shall Statement	Verification Success Criteria	Verification Method	Facility or Lab	Performing Organization	Results
6	CDD	2.3.6	The SERPENT's head section shall be made up of an ultrasonic drill bit and a conical auger	this requirement is under the jurisdiction of the LA Tech Team and will be verified by them.		other	LA Tech Team	not met
7	CDD	2.3.7	The SERPENT shall utilize an elastic water-tight skin to protect the interior electrical and mechanical systems from the fine particulate matter	the skin does not degrade after extended interaction with the soil simulant.	1. skin abrasion test 2. water test	UAH	UAH Team	not met
8	CDD	2.3.8	The SERPENT shall incorporate the space to include a navigational and sensory package	this requirement is for the support structure, therefore has not been designed for yet.	this requirement has no verification method at this time.	UAH, other	UAH Team, LA Tech Team	not met
9	CDD	2.3.9	The SERPENT shall be capable of returning to the surface to deliver the soil samples	The body linear actuators compress and extend to form the peristaltic motion	full test of hardware burrowing vertically	UAH	UAH Team	not met

Table 6: Requirements Verification Matrix (continued)

REQ No.	DOC.	Paragraph	Shall Statement	Verification Success Criteria	Verification Method	Facility or Lab	Performing Organization	Results
10	CDD	2.3.10	The SEPRENT shall be capable to survive multiple missions of burrowing 15 m then ascending back to the surface	1. The linear actuators do not degrade after extended use. 2. the skin does not degrade after extended interaction with the soil simulant.	1. linear actuator test 2. skin abrasion test 3. full system test 4. vertical burrowing test	UAH	UAH Team	not met
11	CDD	2.3.11	The SERPENT should apply mechanical force by means of motors or actuators situated perpendicular to its longitudinal axis	The body linear actuators compress and extend to form the peristaltic motion to propel the SERPENT forward.	1. linear actuator test 2. compression test of strips	UAH	UAH Team	Met
12	CDD	2.3.12	The SERPENT shall be analyzed using modeling and simulation techniques prior to prototype testing.	it was decided during the conceptual design phase to focus more on sample testing instead of theoretical models.		UAH	UAH Team	not met
13	CDD	2.3.13	The SERPENT auger shall be designed to optimize soil displacement and forward motion	this requirement is under the jurisdiction of the LA Tech Team and will be verified by them.		other	LA Tech Team	not met
14	CDD	2.3.14	Individual dummy segments shall be between 50% and 90% of locomotion segment volume	this requirement is under the jurisdiction of the LA Tech Team and will be verified by them.		other	LA Tech Team	not met

Table 6: Requirements Verification Matrix (continued)

REQ No.	DOC.	Paragraph	Shall Statement	Verification Success Criteria	Verification Method	Facility or Lab	Performing Organization	Results
15	CDD	2.3.15	The SERPENT shall produce at least 66 N of force directed perpendicular to the segment's longitudinal axis at the center hinge	The body linear actuators compress and extend to form the peristaltic motion	linear actuator test	UAH	UAH Team	Met
16	CDD	2.3.16	The SERPENT shall be designed to withstand temperature extremes on the lunar surface	1. the skin does not deform or melt due to applied heat. 2. the skin does not degrade from fillings using the soil simulant.	1. flame skin test 2. skin abrasion test	UAH, other	UAH Team, LA Tech Team	not met
17	CDD	2.3.17	The SERPENT shall be provided with electrical power through the use of a cable extended from the surface	The body linear actuators compress and extend to form the peristaltic motion	linear actuator test	UAH, other	UAH Team, LA Tech Team	Met
18	CDD	2.3.18	The SERPENT shall be tested at the KSC test bed in May 2012	The team travels to KSC to preform testing.	full scale test at KSC	UAH	UAH Team	not met
19	CDD	2.3.19	The brackets attaching the linear actuators to the bulkhead will allow for 3 dimensional movements	the brackets were found to be within susceptible limits without redesign.	this requirement has no verification method at this time.	UAH	UAH Team	not met

18. Appendix G: Team Poster

Figure 36: Team 2 Poster

Photo provided by M. Brown