Northeastern University – Students for the Exploration and Development of Space

COBRA:
Crater Observing Bio-inspired Rolling Articulator

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Quad Chart

COBRA: Crater Observing Bio-inspired Rolling Articulator

Concept Synopsis

- COBRA is a modular 11-degree of freedom snake inspired robot for exploring Shackleton Crater
- COBRA will leverage snake locomotion to traverse slippery and porous regolith
- COBRA will tumble down the steep crater slope to efficiently cover large distances
- COBRA will measure regolith ice content using a spectrometer stored in its tail

Innovations

- Novel multimodal mobility concept for permanently shadowed craters
- New crawling and sidewinding gaits
- Optimization of module structure for combined sidewinding and tumbling locomotion
- Design of latching mechanism for reversibly transforming between sidewinding and tumbling modes
- Method for transforming between sidewinding and tumbling

Verification Testing and Conclusions

- Constructed ⅓ scale and full scale COBRA prototypes
- Verified sidewinding locomotion on flat solid and porous sand
- Verified transformation into and out of tumbling mode on slopes and flat ground
- Demonstrated tumbling down 35 degree slopes with ⅓ scale system and 8 degree slopes with full scale system

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1.0 Executive Summary

The Northeastern University BIG Idea Team presents COBRA, the Crater Observing Bio-inspired Rolling Articulator. COBRA is a novel snake-inspired mobility system that combines slithering and tumbling locomotion to traverse Shackleton Crater to measure water concentration for future in-situ resource utilization efforts.

First, COBRA will be deployed from a lander close to the edge of Shackleton Crater. COBRA has 11 degrees of freedom which allow it to perform a variety of locomotion methods and motions. From the lander, COBRA will utilize sidewinding to reach the crater's edge. The term sidewinding describes a special type of snake locomotion used on porous and slippery substrates such as sand. The sidewinder snakes make use of vertical and horizontal waves that travel down the length of their body to efficiently move over sand to minimize sinkage and slippage. Once at the crater's edge, COBRA will rigidly connect head to tail using a latching mechanism to transform into a hexagon for tumbling. Next, COBRA will shift its mass forward to initiate tumbling down the steep 30.5 degree slope of Shackleton Crater. Now, COBRA uses minimal energy to maintain the hexagon and leverages lunar gravity to quickly travel down the crater slope, similar to a tire being pushed down a hill. Additionally, if COBRA falls over or wants to stop tumbling, it can simply disconnect its head and tail to return to sidewinding mode and reorient itself. Upon stopping, COBRA can use a mass spectrometer stored in its tail to scan for volatiles on or below the surface, namely water.

We have designed and built a fully functional prototype of COBRA weighing 7.11 kilograms and totalling 1.59 meters in length. We have successfully performed verification testing that demonstrates all stages of our mission. First, we have demonstrated sidewinding motion on flat ground and in sand. The sand is the earth analog to porous lunar regolith and this verifies the first step of our mission, sidewinding from the lunar lander to the crater's edge. Next, we have verified transforming into and out of tumbling mode on the edge of a flat pavement slope. Lastly, we verified shifting our center of mass to initiate tumbling down a slope and sustained stable tumbling down a 4-8 degree decline slope. The system is passively stable during tumbling due to the gyroscopic effect and a wide frame. We also performed extensive tumbling tests with a ⅓ scale system called COBRA Mini. We tested his system on 4-35 degree slopes and verified tumbling stability for all slopes . Also due to the gyroscopic effect, as the angular velocity increases, the system becomes more stable. Based on these results, we are confident the full COBRA system can tumble down steeper slopes up to and beyond the 30.5 degree slopes found in Shackleton Crater. These developments have increased the TRL of the system from an idea (Level 2) to functional breadboard prototype (Level 5) with extensive testing of critical operations in relevant environments. These demonstrations significantly de-risk key aspects of our concept and the system is ready for performing the full operation in sand and eventually lunar regolith simulant. We have already demonstrated a sheath that prevents dust infiltration with sidewinding in sand and have designs for protecting the head and tail latching mechanism. Based on the verification testing for critical subsystems and having already selected materials for a flight version of COBRA, we are confident the system could perform in the targeted environment.

The COBRA system demonstrates a novel combination of locomotion methods that creates new possibilities for exploration of extreme lunar terrain. Our system presents a low-cost, lightweight and energy efficient method to explore permanently shadowed regions (PSRs) as soon as 2024. With access to PSR's we can develop detailed maps of volatile concentration and begin targeted in-situ resource utilization (ISRU). The ability for ISRU is a key enabling step in maintaining a permanent presence on the moon.

2.0 Problem Statement and Background

With the Artemis program, NASA and collaborating space agencies aim to revitalize Lunar and space exploration. An Artemis objective is to create a sustainable human basecamp on the Moon in the hope of propelling further missions to Mars and beyond [1]. Accomplishing such a feat is contingent on In-Situ Resource Utilization (ISRU) on the Moon. One resource of significant interest is Lunar Ice/Water which can potentially supply drinking water, oxygen, and rocket propellant. However, the means to access the ice deposits on the Moon still require additional development [2].

In 2018, NASA confirmed the presence of water ice on the Moon's poles, concentrated mostly in Permanently Shadowed Regions (PSRs) [3]. The near-permanent lack of sunlight in these regions results in extremely low temperatures (as low as -238 ºC) and allows for the accumulation of water ice and other volatiles [4]. Interestingly, there are areas of near-constant illumination near some PSRs. One such PSR is the Shackleton Crater, whose environment is of primary interest to this article [5].

While the presence of "water ice" in Shackleton is evident, there are no precise measurements of its quantity or its chemical composition. In addition to more detailed observations of water content in PSRs, information on mineral concentrations and topographic maps of crater terrain are important, which requires more proximate investigations [6]. With such acquired information, targeted mining operations can be initiated to commence ISRU. However, these regions pose environmental challenges to scientific exploration that must be addressed by an effective mobility solution.

The first mobility challenge consists of high porosity regolith found on the South Pole and in the Shackleton Crater. Due to the regolith's high porosity, traditional wheeled rovers suffer sinkage and slipping, therefore reducing energy efficiency and increasing risk of immobilization [7]. The second challenge is traversing the immense slopes to reach all areas of scientific interest inside the Shackleton Crater. It is a massive geographic feature, 21 kilometers in diameter. The crater slope leading to the crater floor has an average slope of 30.5 degrees and covers a horizontal distance of approximately 8 kilometers [8]. The steep slope makes both ascending and descending difficult. On the descent there is limited traction, and the regolith substrate is more prone to yielding, leading to slipping and sinkage. These factors also make it incredibly difficult to ascend the slope and state-of-the-art rovers can only climb a maximum of 30-degree inclines as they rely on sufficient friction with a surface. The third challenge is traversing uneven terrain inside the crater and surrounding area. The crater slope and floor have a root mean square (RMS) surface roughness of approximately 1 meter [9]. As such, wheeled systems struggle to traverse as the height of the obstacle they can overcome is limited by the diameter of their wheels. Additional mobility challenges include boulder fields around the crater and the unknown mechanical properties of regolith with ice.

The lack of sunlight poses two challenges: power generation and near absolute zero temperature. Traversal of the crater is limited due to the lack of solar power; therefore, large distances must be covered with minimal power consumption. Low temperatures interfere with mechanisms that rely on lubricants as well as liquid batteries. This results in less efficient power systems. The high porosity lunar dust is also abrasive and invades machinery due to its particulate nature. Overexposure to porous lunar dust without proper mitigation strategies can quickly turn a mobility solution futile. Additionally, due to the lower temperatures in the PSRs, inner-crater regolith properties and their effects are not fully understood. Moreover, the lack of detailed topography of the crater floor makes navigation particularly difficult on rough irregular surfaces [10]. To overcome these mobility challenges, a system must be designed with an emphasis on limiting or overcoming sinkage and slippage along with features to prevent immobilization. Most importantly, the system must traverse these environments in an energy efficient manner. It should also have both passive and active regolith mitigation strategies for longevity and performance.

One solution to traversing steep slopes is to equip wheeled systems with tethers, such as the DuAxel system [11]. However, the size of the slope of Shackleton crater reduces the effectiveness of these solutions. To reach the center of Shackleton crater a tether many kilometers long would be required. Another solution to the traversal of steep slopes is legged systems. These systems can modify the angle of their legs externally from the orientation of their body, meaning they do not rely on friction forces for movement. However, similarly, to wheeled systems, the high porosity regolith causes significant sinkage of the foot, leading to instability and inefficiency. While a thruster-based hopping system might seem appropriate for covering such a large area, their exhaust may change the chemical composition of the ground that they land on, which would interfere with scientific investigation. Traditional mechanical hopping systems will have difficulty launching from the low-density regolith and are at risk of landing incorrectly and becoming damaged or stuck. One system that can take advantage of steep inclines is tumbling systems. A tumbling system utilizes gravity to travel down a slope, which requires no additional actuation, leading to extremely energy efficient travel. In many cases tumbling systems are paired with another locomotion method, such as NASA's Hedgehog robot, which combines tumbling locomotion with hopping. This system utilizes internal reaction wheels and is designed primarily for exploration of comets and asteroids [12]. While the system is robust and efficient, the actuation method and size of Hedgehog limits the distance it can travel, payload capacity and scientific operations it can perform.

To address the mobility challenges and the weaknesses of existing solutions, the COBRA system combines two types of locomotion: tumbling and slithering. Through tumbling down the steep slope of Shackleton Crater gravity's energy is harvested to travel large distances with zero power consumption. By combining tumbling with the multiple degrees of freedom of a snake-like system, we gain the ability to perform articulated scientific operations, large payload capacity, and robust maneuverability in porous and irregular terrain. The symmetric body of a snake system makes it excellent at traversing uneven and unknown terrain, by virtue of not needing to reorient itself. Additionally, the weight of the system is distributed along the entire length of its body which mitigates sinkage.

3.0 Project Description

3.1 Concept of Operations

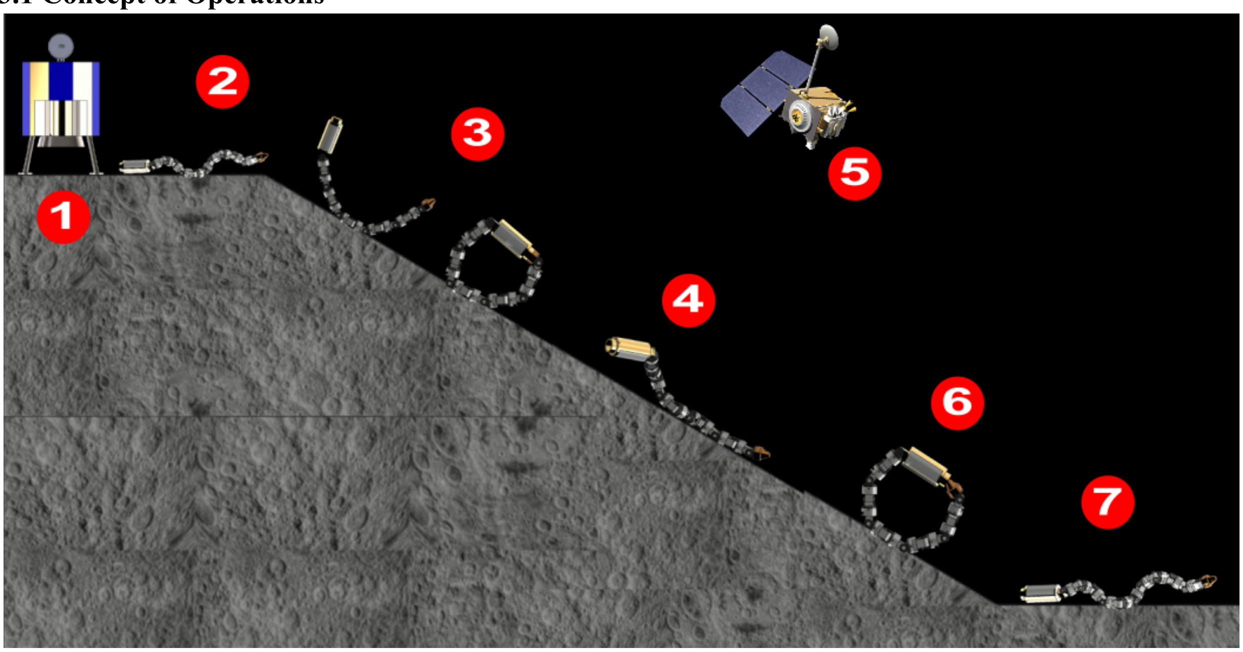

Figure 1: Concept of Operations

1) The mission scenario begins with a CLPS lunar lander deploying the COBRA close to the edge of Shackleton Crater.
2) Once deployed, COBRA will maneuver to the slope of the crater utilizing sidewinding. Sidewinding is a form of snake locomotion utilized to traverse loose and slippery substrates such as sand dunes. In sidewinding, limbless body segments are lifted and shifted forward while other body segments remain static and in contact with the ground. This method of locomotion reduces the shear forces applied at contact, which helps prevent slipping on yielding surfaces such as sand or regolith [13].

3) After sidewinding to a slope, the system will take advantage of the lunar gravity by tumbling down the steep crater slope. The tumbling is achieved by COBRA self-connecting the head and tail modules into a near circular shape. Once connected, the system can shift its weight forward to initiate tumbling. Once in movement, its joints can remain static, reducing energy consumption. The mechanisms behind the tumbling are described further in a later section.
4) Once in tumbling mode, COBRA will travel down the crater incrementally, stopping every 500 meters to disconnect its head and tail to perform in-situ measurements. COBRA's scientific payload consists of a spectrometer located in its tail. The spectrometer can be positioned and aimed at specific targets utilizing the joints in the body. The system will be able to create a detailed hydrogen concentration map at different depths within Shackleton Crater.
5) After performing measurements, it will send the results to the lunar reconnaissance orbiter (LRO) utilizing a radio antenna stored in the head module of the system. By transmitting results to the lunar orbiter, COBRA does not need to expend energy climbing out of the steep crater.
6) When the communication at the sampling location is completed, it returns to the circular formation and tumbles another 500 meters and repeats the process.
7) Lastly, after traversing the slope of the Shackleton Crater, the system will explore the flatter center of the crater utilizing sidewinding, where it will continue to take measurements until all available power is exhausted.

3.2 Project Lifecycle

Based on the NASA System Engineering Handbook, we are nearing the end of Project Phase A. [14]. We have developed a breadboard prototype based on system-level requirements and a finalized mission concept. We selected and developed our key system technologies, including optimal geometry for both sidewinding and tumbling locomotion, latching mechanism to enable reversible transformation to tumbling mode and stable tumbling down slopes. We have also developed a preliminary verification and validation plan. By following this plan, our prototype has achieved in reducing the high risk of the aforementioned components, demonstrating that a feasible design exists. Currently, we are finishing verification and validation, then we will analyze and identify new project risks for Phase B and beyond.

3.3 COBRA Mini

3.3.1 Motivation

In order to validate and begin testing our mobility concept quickly and inexpensively, we first designed and built COBRA Mini (Fig. 2A). COBRA Mini is an approximately ⅓ scale replica of the actual COBRA system, designed to test movement concepts synchronously with the fabrication of the larger COBRA system. This has allowed us to identify flaws and alter the larger system throughout its development.

3.3.2 Mechanical Design

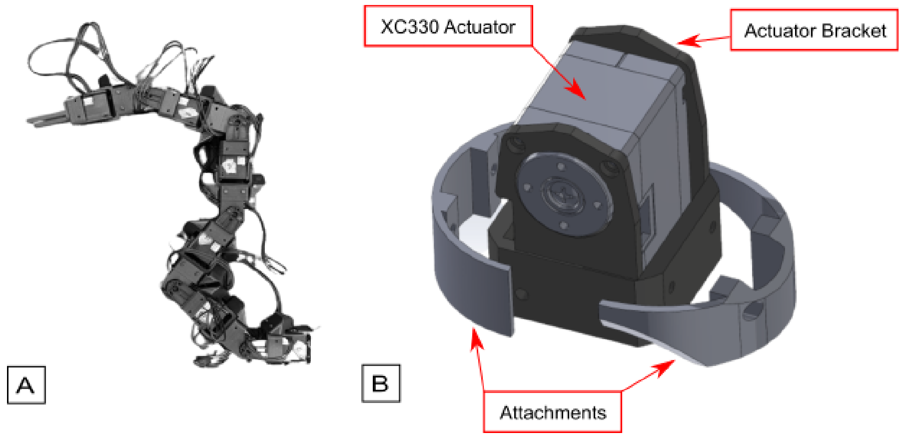

Figure 2: (A) COBRA Mini Full Body. (B) Close-up of Single Module with XC330 Actuator, Actuator Bracket and Interchangeable Attachments. These attachments were used to rapidly experiment with different exteriors to determine the best shape for sidewinding and tumbling.

To create COBRA Mini, Dynamixel XC330 actuators were used in conjunction with actuator brackets and various interchangeable geometry attachments. 11 Modules were fabricated along with a static, mock latching mechanism used to transition between tumbling and sidewinding. The length of this mechanism is consistent with that of the scaled expected payload module. As seen in Fig. 2B, actuator brackets were designed to allow for interchangeable external geometry attachments on the system. Differently shaped attachments were used to target our individual mobility solutions. Circular, elliptical and square attachments were tested to determine the shape to optimize sidewinding and tumbling configurations.

3.3.3 Electrical Design

The power delivery system for Cobra Mini is simple, as the power demand for these smaller motors is within a range where we can use a central power supply to power the chain of 11 motors. The stall current draw for each of the XC330-M181 motors is listed in the datasheet at 1.80A and the mass of each motor (which dictates the load displaced by the motors) is only 23g [15]. After having done tests to determine the current draw under the expected load, we determined we could power the entire chain of motors with two 5V, 3A outputs of a power supply connected in parallel. Using a 2 meter cable for power, we could perform all necessary testing with COBRA Mini without necessitating on-board power architecture.

3.3.4 Software Design

COBRA mini software consists of a set of Python classes and scripts that interact with the Dynamixel SDK to actuate motors and monitor data. The Python interpreter used is 2.7.18, meant for future integration with ROS Melodic. The program is run on an external laptop through a keypress interface to monitor and debug the software in real time. Design choices of ROS Melodic integration and the Dynamixel SDK were made for extensibility on the full scale platform. COBRA mini served as an important test bed for exploring alternatives to sidewinding from the algorithm shown in the proposal. The algorithm in use to perform sidewinding in the Simulink footage used in the proposal submission was using a divide-and-conquer algorithm to estimate the angles between each segment of an N-bar linkage that had a wave passing through it. That approach would produce an array of angles to be fed to the simulation at a frequency of 100hz, which proved to be too high of a data transfer rate for the physical platform. COBRA mini implemented a new algorithm to only issue motor data writes strictly for peaks and troughs of the waves, which had a reduced frequency of data transmission. This new sidewinding approach was used in the software design for the full scale model. COBRA mini's software suite also had features for hexagonal transformation, hexagonal center of mass tilting, and spiral transformation which were also brought forward to the current platform.

3.4 COBRA

3.4.1 Mechanical Design

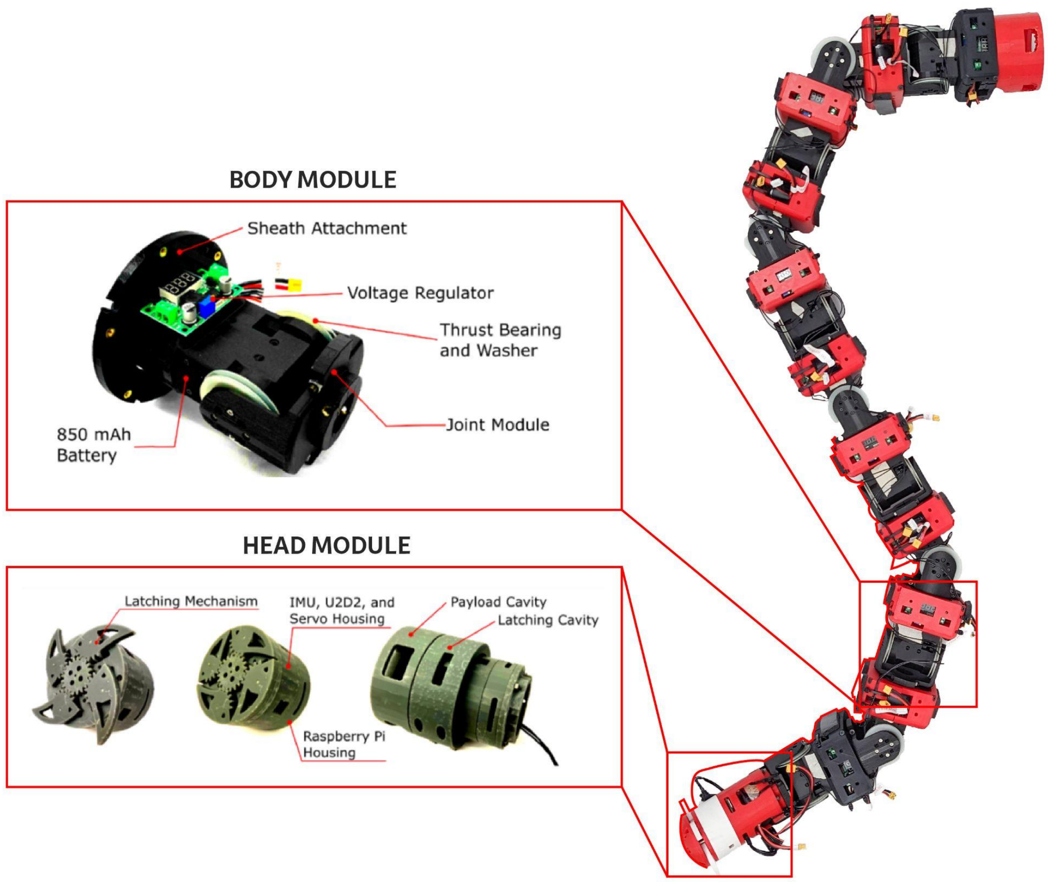

Figure 3: Full Body of COBRA with 11 identical joint modules, head/tail modules and all components.

As shown in Fig. 3, the full COBRA system consists of 11 identical modules each with their own actuator, voltage regulator, and battery, along with a head and tail module. The total length of the system is 1.59 meters and 7.11 kilograms. For the full-scale COBRA system, we utilized the Dynamixel XH540-W270 actuators based on their high torque-to-weight ratio. These motors provide a maximum torque of 9.9 newton-meters at the recommended 12 volts [16]. This provides a safety factor of approximately 2 for our maximum expected torque: the transformation from slithering to tumbling mode. We utilized Markforged 3D printers to fabricate the modules with Onyx, a material that combines carbon fiber with nylon leading to extremely strong and lightweight structures. A single module is split in half for printing and assembly and is connected using 3 bolts. The module also features two needle-roller thrust bearings to handle axial loads while the radial bearings in the actuators are already sufficient. The thrust bearings are held between two washers with grease to reduce friction between it and the 3D printed parts. Each module also includes a battery and voltage regulator for powering the actuator. Next, cables run between each module to daisy chain the actuators to the head module which contains the motor controller. An external attachment protects the voltage regulator and battery connector as well as directing cables between modules neatly. The modules feature a symmetrical 4 bolt pattern that joins the male joint section with the female housing section of the next module. A total of 11 modules are connected in alternating vertical and horizontal direction to assemble the whole COBRA system. A single assembled joint module weighs 592 grams and can move a full 180 degrees.

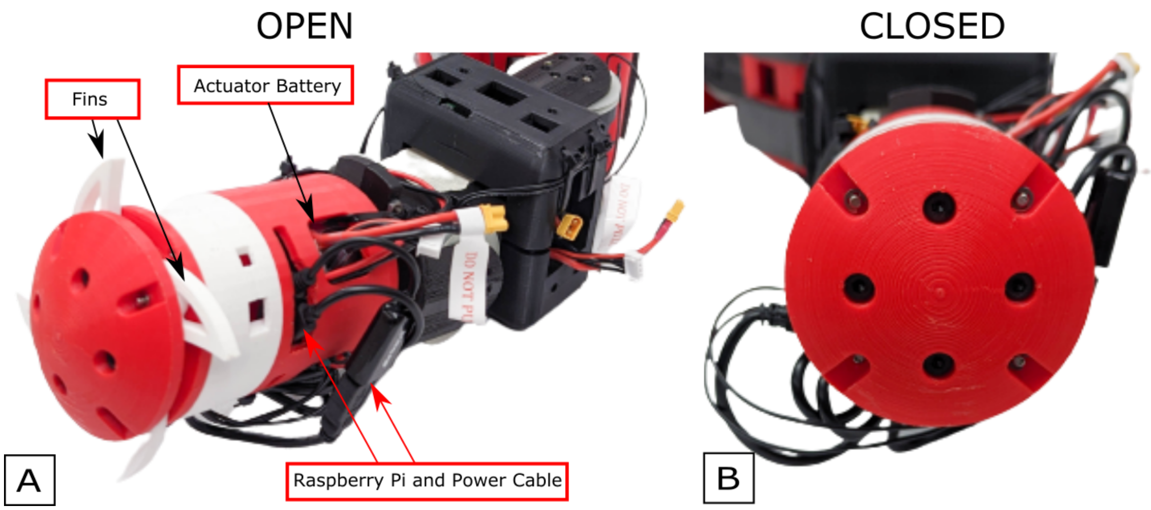

Figure 4: (A) Head Module with latching fins open. (B) Head module with latching fins closed.

In addition to the 11 identical modules, COBRA features a distinct module at the snake's head, aptly referred to as the "head module," and similarly, a "tail module" at the snake's tail end. The primary purpose of these unique modules are to connect together to form a loop prior to the onset of tumbling mode. The head module acts as the male connector and utilizes a latching mechanism to sit concentrically inside the female tail module. COBRA's head module also houses a Raspberry Pi Zero W (along with a LiPo battery for power and its accompanying voltage regulator), an inertial measurement unit (IMU), and the Dynamixel U2D2 motor controller.

The latching mechanism, shown exploded in Figure 5, consists of a Dynamixel XC330 actuator, as used in COBRA Mini, which sits within the head module and drives a central gear. This gear interfaces with the partially geared sections of four fin-shaped latching "fins." The curved outer face of each latching fin has an arc length equal to 1/4 of the circumference of the head module's circular cross section. When the mechanism is retracted, these four fins form a thin cylinder that is coincident with the cylindrical face of the head module. A dome-shaped cap lies on the end of the head module so that the fins sit between it and the main body of the head module. Clevis pins are used to position the fins in this configuration. COBRA's tail module features a female cavity for the fins. When transitioning to tumbling mode, the head module is positioned concentrically inside the tail module using the joint's actuators, and the fins unfold into the cavity to lock the head module in place. For the head and tail modules to unlatch, the central gear rotates in the opposite direction, and the fins retract, allowing the system to return to sidewinding mode.

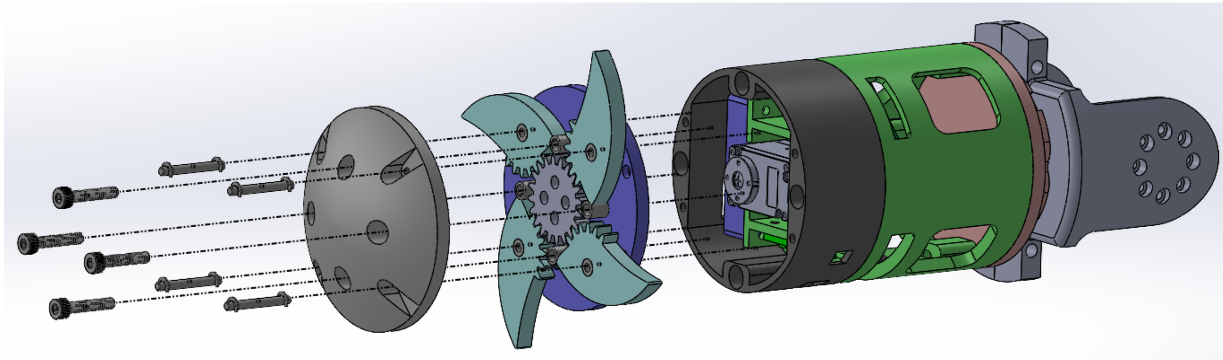

Figure 5: Exploded View of Latching Mechanism with Head Module Components

The choice for an active latching mechanism design stemmed from the design requirements and restrictions. Magnets were initially discussed as a passive latching option, however they would not be effective in conjunction with the ferromagnetic regolith. Further, due to the need to stay in a latched configuration even when a large amount of force is applied to the system during tumbling, a passive system was not chosen, for there would be the risk of unlatching during tumbling. The chosen design connects the head and tail modules fairly rigidly and minimizes the possibility of latching failure during tumbling. Shear load on the latching fins was considered through rough analysis of the maximum shear stress of different configurations of carbon fiber reinforcement layers within the 3D-printed parts. Ultimately, these fins were designed to be sufficiently thick - 6mm - and include three, equally spaced layers of carbon fiber reinforcement, each a few layers thick. This latching mechanism design was also chosen for its ability to be dust proofed through close clearancing (running fits) between the fins and the cap and latching plate, so when the fins are closed, there is little to no gap to enable dust infiltration.

The tail module is the intended location to house the payload. The Puli Lunar Water Snooper (PLWS) was chosen as COBRA's payload. The PLWS uses 3 MOTS sCMOS image sensors (thermal neutrons, epithermal neutrons and a reference sensor) as detectors. The PLWS is a low-cost, COTS-based system with an FPGA. It has an envelope of 10cm x 10cm x 3.4cm and a mass of 382g, making it a small lightweight scientific payload that can fit within the tail module of COBRA. The PLWS can allow for significant scientific readings throughout COBRA's mission scenario. Currently COBRA's tail module includes a small compartment in which weights can be placed to simulate the presence of this payload for future testing.

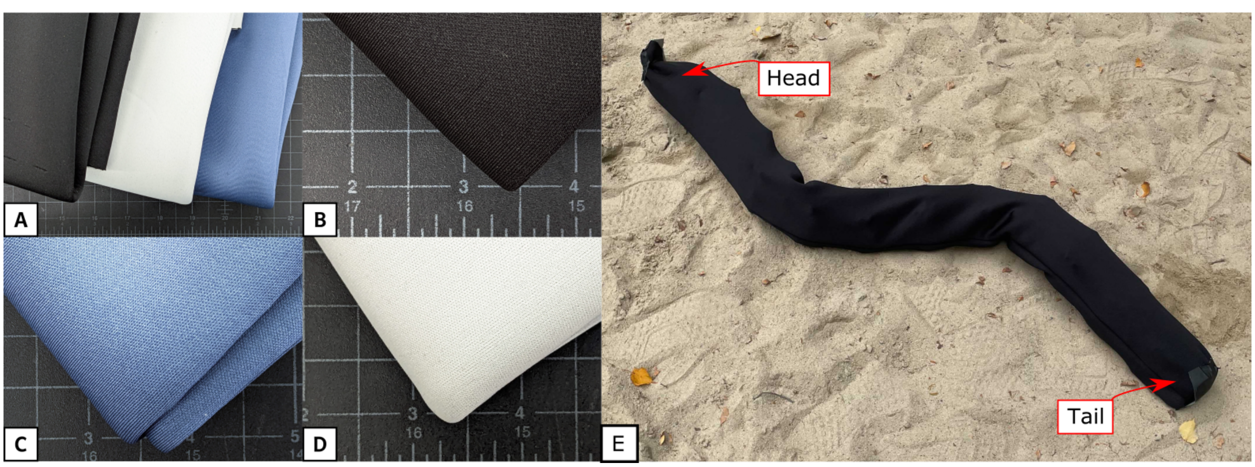

Figure 6: (A) Sheath Materials Closeup (B) 3 mm Neoprene Fabric (C) 2 mm Neoprene Fabric (D) Closed Cell Bonded Neoprene (E) 3 mm Sheath on COBRA

As COBRA is meant to work in highly porous and abrasive lunar regolith it is essential that these fine particles do not infiltrate the system and impair joint movement. To protect against this, a tubular sheath was implemented to cover the system's main body from head to tail. The idea of having individual sheaths for each module was explored, however, due to increased complexity and chances of failure, a longer, single sheath was decided on. The sheath is a 1.62 meters long fabric that has one seam to make it a 390 mm diameter tube which tightly fits over the system, while not being too tight to interfere with joint movement. Understanding the abrasiveness of regolith and the risk of having holes in the sheath, the fabric must have high abrasion resistance and durability. The ones that are being explored are: 2 mm neoprene, 3 mm neoprene, closed cell bonded neoprene, and urethane coated polyester. Neoprene has high tear and abrasion resistance while having flexibility that allows for free joint movement. Urethane coated polyester fabric likewise has high tear and abrasion resistance, however, has very minimal flexibility. This fabric has similar mechanical properties to Kevlar and Vectran which are likely candidates for further iterations of the sheath, depending on how polyester performs compared to the neoprene fabric.

To prevent any regolith from interfering with the head and tail modules, two methods of protection are being ideated for both ends. For the head, a skin concept with material that is more flexible than the body's sheath is being pursued that both protects the latching mechanism while allowing the blades to fan out fully. As for the tail and its female cavity, an iris diaphragm concept has been ideated to act as a door (not included in figure above). For this mechanism, a co-centered outer ring is turned by a servo with respect to an inner ring, which turns the iris blades between them. One end of each iris blade is attached to the outer ring by a pivot assembly and the other to the inner ring by a slider assembly. Thus, as the outer ring turns, the blades will both slide and turn to either open up or close off the cavity to allow the head to enter and exit with minimal regolith interference.

3.4.2 Electrical Design

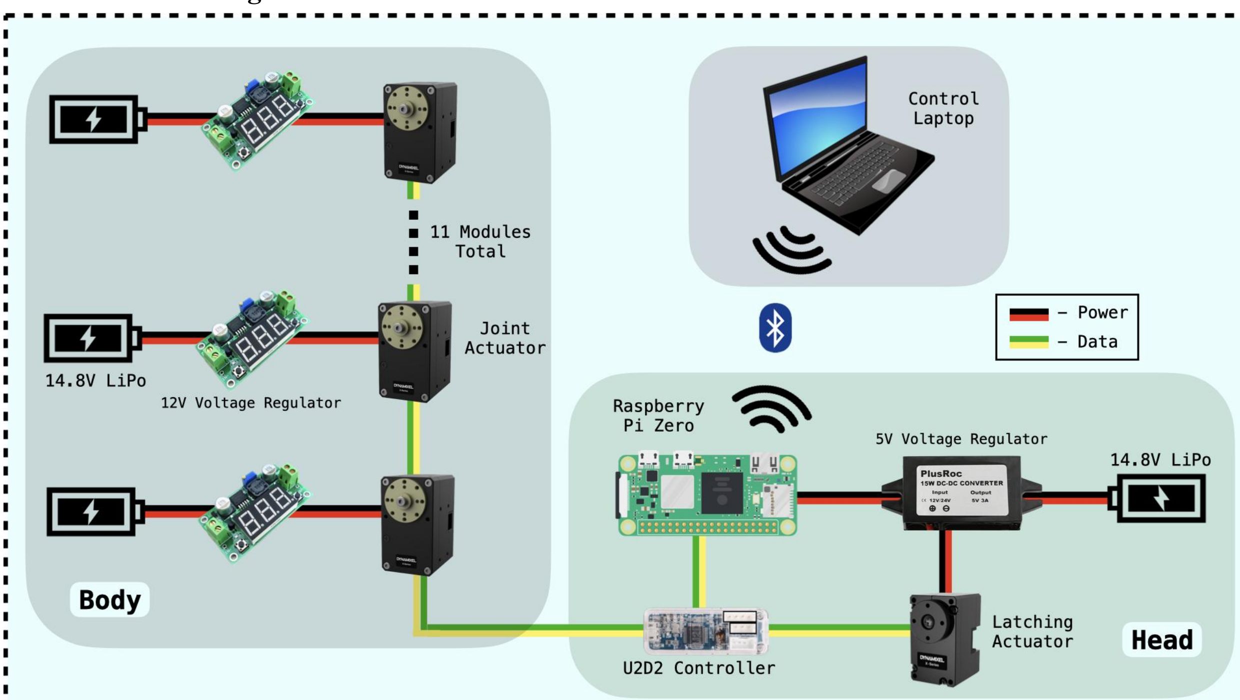

Figure 7: Electrical Architecture for COBRA

The power distribution topology of COBRA is defined in Figure 7. With this topology, the weight of the supplied power is distributed evenly. Inside each module, individual batteries are connected through a voltage regulator to each actuator. This design simplifies power draw calculations and contributes to the modularity of the system. Any number of modules can be added or removed without affecting the overall functionality. This power distribution topology is also resilient to the failure of one or more of its individual modules, providing an extra layer of fault tolerance. To power the actuators, GensTattu 850mAh 14.8V LiPo batteries were chosen as they are fairly light (107g) and easily fit inside the module (60mm x 30mm x 30mm), while also providing a run time of 17 minutes at an average current of 3A.

Within the electrical architecture of COBRA there is room for the implementation of radar sensors and an IMU. To integrate an IMU, a microcontroller will be connected to the Raspberry Pi via micro USB. With the IMU attached to the microcontroller, the acceleration, angular velocity, and orientation of COBRA can be recorded by the Pi. This data will be especially useful in tumbling mode, as COBRA will be able to autonomously detect when it has fallen over. When this is detected, COBRA will be able to unlatch and reconfigure itself into hex mode to continue the tumbling motion. As COBRA is unlatched, the radar sensors can be utilized to map the surrounding area. These will be wired to a connector board that is compatible with the GPIO pins on the Pi. With COBRA's unique movement capabilities, the radar sensors can be implemented in a range of applications.

So far, both the radar sensors and the IMU have been individually tested using manufacturer-provided software. These tests have produced accurate signals and positional data. Although the sensing infrastructure has yet to be developed onboard COBRA, integration should be seamless due to the pre-existing electrical framework.

3.4.3. Software Design

Changes to the COBRA Mini software design emerged out of needs for remote connection and considerations for the test environment. These changes include the use of Bluetooth and the VNC viewer client to enable SSH (secure shell protocol) operation of the Raspberry Pi computer on the snake body. Software explored for sensing includes implementations of ROS subscriber and publisher nodes for accessing the IMU. COBRA software also includes extended functionality to account for the latch motor during hexagonal transformation, as that motor is not present on the smaller scale model.

Additionally, for use with SSH control of the platform, COBRA has a keypress control program with a text-based UI and additional messages for debugging. COBRA's software suite also has a set of controller classes that encapsulates movements like sidewinding and transformations into callable class methods that can be called by our keypress control class or included in other implementations of a control application. These controller classes are divided based on the actions that they execute, whether it be sidewinding, transforming, tumbling, or surveying. Controller classes share a reference to a state object that allows each class to identify which state the overall system is in, even if the current state is outside the scope of a class's responsibilities.

COBRA's controller class methods can be used by another application that could support autonomy in the near future. However, development of path planning and decision making was determined to be outside of the scope of team member capabilities due to schedule constraints. The current plan for sensor and mobility integration is to use the IMU orientation readings to determine the correct sequence of joints to shift the snake's center of gravity forward in hexagonal form. Currently the software does not have this feature integrated, but the hexagon center of mass shifting function has been tested extensively with successful results, albeit from a fixed starting orientation.

3.5 Integration with External Systems

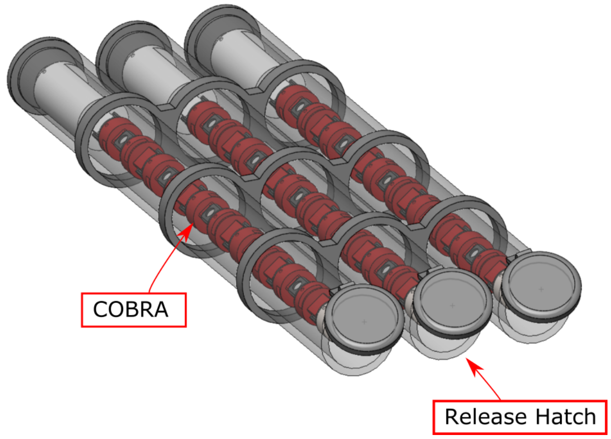

Figure 8: Stowage on Lunar Lander and Communication Strategy

The slender frame, multiple degrees of freedom, and low mass of our system enable many options for stowage. Our current system is already compatible with the Peregrine Lander from Astrobotic Technology, thanks to its small length and diameter [17]. The lander is slated to launch on United Launch Alliance's Vulcan Centaur Rocket. Another design for the COBRA stowage mechanism, one that particularly lends itself to future scalability, consists of a hollow cylinder or tube where one end opens like a door to deploy the device. Multiple of these systems can be connected, as shown in Figure 8.

Our proposed communication solution is based on a tried-and-true method used by NASA's Curiosity and Perseverance rovers. A 434 MHz UHF radio transceiver and antenna capable of communicating with NASA's Lunar Reconnaissance Orbiter will be included in our system for the flight version. While the periapsis of the Mars Reconnaissance Orbiter is 255 kilometers above the south pole of Mars [18], the periapsis of the Lunar Reconnaissance Orbiter is only 20 km above the moon's south pole as of 2015 [19]. Our system will have a much shorter distance to communicate over, meaning our transmission module at a frequency equal to that used by the Orbiter and have an acceptable data transmission rate at 300 kbps. The lunar orbiter will then relay the data, downlinked at 100 Mbps, through a single Ka-band ground station at White Sands, New Mexico, USA. [20]. The system uses a wire antenna that is ¼ the wavelength (164 mm) long which is chassis-mounted to the head module. The body of the snake can be re-oriented during data transmission to achieve optimal positioning of the antenna. This approach, opposed to relaying communications to the lander, minimizes the possibility that the signal could be subject to interference by conductive material on the lunar surface by designating the receiver as an aerial target.

3.6 Potential Stakeholders

One potential stakeholder is the Hungarian company, Puli Space, who are developing a compact instrument to measure hydrogen on the moon's surface [21]. Our system will use this instrument to measure water concentration throughout Shackleton Crater, providing an excellent use case and demonstration of their device. As COBRA is playing a crucial role in identifying lunar resources, organizations or companies in industry working in the in-situ resource development space would be interested in any data we find, such as NASA.

4.0 Verification Testing on Earth

Two prototypes, COBRA and COBRA Mini, were developed to assess their locomotive capabilities in a model environment that would resemble some of the main constraints contained on the Lunar South Pole. For instance, sand was used to simulate lunar regolith due to its abrasive and granular structure when testing COBRA. Regolith simulant was not used due to schedule constraints and additional safety protocols needed to maintain the material. Also, we decided to forego simulating the temperature, vacuum, and lower gravity conditions as testing mobility remained a top priority.

To begin the verification process, each individual joint module was tested to ensure it could withstand the maximum expected load. With the full sheath, testing was done to determine its permeability to dust and other microsized grains. Tests for various stages were performed to emulate the steps of the mission scenario. The first stage consists of COBRA sidewinding from the lunar lander to the crater edge. We performed sidewinding on a flat, sandy surface to verify COBRA can perform the first stage of the mission. The second stage involves COBRA transforming into a hexagon shape on the edge of the crater slope. Then, COBRA would shift its center of mass forward to initiate tumbling. We tested COBRA's ability to transform and shift first in the lab, and then outside on 4-8 degree slopes. Due to time constraints we were not able to locate a testing facility with 30.5 degree slopes for the larger COBRA system. However, we were able to test transformation and tumbling with the COBRA Mini system on 4-35 degree slopes. We compared and analyzed tumbling performance across the different slopes and determined the system remains stable even at higher slopes due to the gyroscopic effect and increased momentum. This suggests that COBRA is versatile enough to be considered for a variety of different mission scenarios, as it is able to traverse steep and shallow slopes.

4.1 COBRA Mini

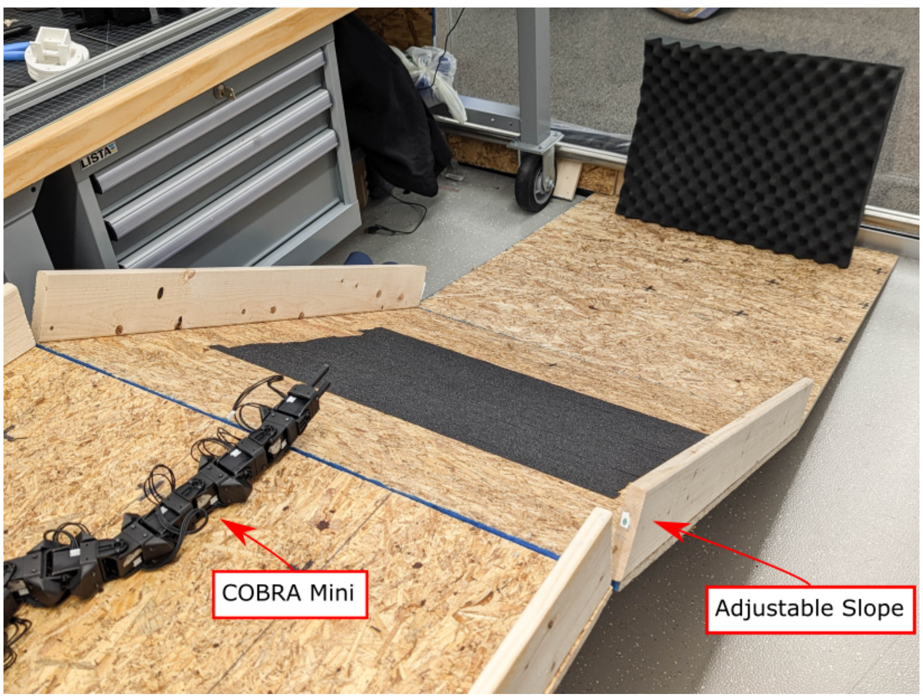

Figure 9: COBRA Mini Testbed

To test the tethered COBRA Mini, we developed an adjustable wooden ramp. The ramp has a 0.5m flat section used for sidewinding and a slope with length 1.5m. On the base of the ramp was a block of foam to ensure the system would not run into the wall or travel far enough to reach the end of the tether. Halfway down the ramp, an abrasive tape was placed to determine the effects of increased friction during tumbling.

To test sidewinding, the ramp was placed horizontally and COBRA Mini was tested for 5 cycles of sidewinding. Both the rotational and lateral movement were tracked. Sidewinding was also tested on smoother surfaces like the table and veneer floor.

To test tumbling, the ramp was placed at 18, 25 and 30 degree angles. COBRA Mini was placed parallel to the ramp such that when it transformed into the hexagon configuration, the bottom module was just before the start of the slope. COBRA Mini was then tilted to increase momentum and tumbled down the slope. Stability in the horizontal and vertical directions was compared for each external geometry attachment. For some tumbling tests, obstacles were placed at various positions along the rampe to determine their impact to the stability of tumbling.

COBRA Mini was first tested without any attachments as a baseline for the success of the system in both sidewinding and tumbling configurations. Then, sidewinding and tumbling were tested using each external geometry. Circular, elliptical, triangular prism and a hedgehog inspired attachment were tested.

During initial tumbling testing, COBRA Mini was not stable and was unable to tumble. However, this was determined to be a combination of the added weight of the tether and the weight distribution of each module. In the actuators used, the gearbox is only on one side of the module. As a result, half of the modules were rotated to decrease the offset of these weight differences. After these changes, COBRA Mini was able to successfully transform and tumble down the testbed.

4.2 COBRA

4.2.1 Sheath

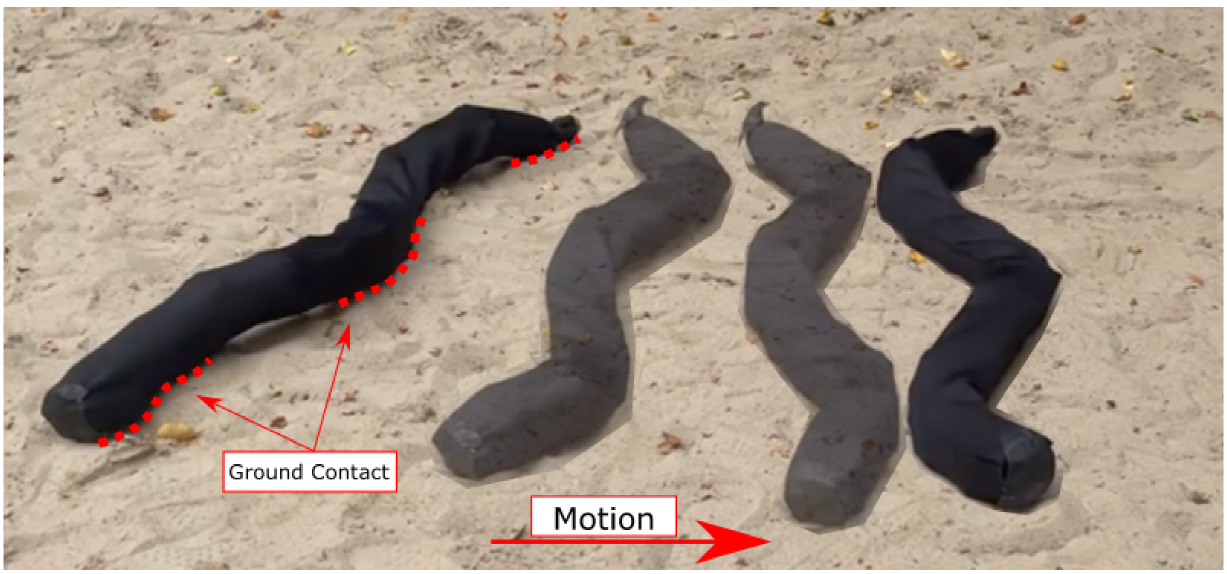

Figure 10: COBRA Sidewinding on flat sand with neoprene sheath

Based on initial sheath tests, the current idea of using a tube shape made of neoprene seems to be a promising plan, as it does not hinder any of COBRA's movements. After running our sidewinding program, we noticed that there was virtually no difference between COBRA's movements with or without the 3 mm neoprene sheath and the same was seen when we transformed into tumbling mode. Further, a relative current sensing test of a Dynamixel motor in a single module was used to measure whether the sheath added resistance to the motor articulation. We found that for angles less than 80° the current sensing values were practically the same as the module with no sheath. At angles higher than 80°, the current sensing values rose exponentially, however, this is not a concern since COBRA's modules are not meant to articulate more than ±70°.

The seam for each neoprene fabric was tested for how well it could keep out fine particles by stretching the seam over a container and pouring fine gravel on top. This was then shaken for a minute and the weight of the container was weighed and compared to the weight prior to pouring the gravel on top. For each of the neoprene fabrics, there was no change in weight before and after the test, meaning the seam does not allow for any particles to pass through.

4.2.2 Sidewinding

Similar to COBRA Mini, the first sidewinding tests occurred on smooth veneer floors indoors. The horizontal wave had an amplitude and period of 60 degrees and 4.3 seconds respectively. The vertical wave had an amplitude of 30 degrees and period of 4.3 seconds. The motion lasted for 17.2 seconds. The system had difficulty translating and instead rotated 180 degrees. The second test involved the same sidewinding gait but occurred on a rug to increase friction. Further tests experimented with modifying wave amplitude and period to 75 degrees for the horizontal wave and 30 degrees for the vertical wave and 2.5 seconds. The outdoor sidewinding tests occurred on pavement and on sand. For the sand testing to verify movement in a porous environment, three inches of loose sand on top of five inches of packed sand was tested. The lateral movement seen on sand was comparable to that on pavement, with little to no sinkage into the sand during movement.

While testing sidewinding, a few different methods of motion were used. The gait generation algorithm used in the simulation resulted in numerous issues in communication bus bandwidth, and so design for COBRA's software includes two new techniques. Motion A uses a multithreaded approach to run a cyclical sine wave function in each motor in a staggered fashion to imitate a wave passing through the snake, and motion B uses a fixed 2D array of joint angles for each motor to run through row by row, with each row being executed at once within a certain timestamp.

Both of these methods involved representing wave-like motion with the motors directed to move to only the peaks and troughs of the sine wave moving down the length of the snake. However, these methods differed in their implementation for threading and synchronization. Motion A uses threads running the pattern generation function that generates waves with a certain amplitude and period that are started at different phases of the wave, and is more extensible in how these wave functions and their start times can have specific tweaks to affect specific motors. Motion B runs on a single thread and uses Dynamixel SDK's built-in sync write function to publish a predetermined set of joint positions to the motors at the same time. Theoretically, motion A should be fully capable of achieving everything motion B is currently capable of doing, but hasn't had the time to be fully fleshed out. Motion A showed smoother movement, however was more susceptible to slipping and the system rotated in place. On the other hand, Motion B did not slip and was able to create lateral movement, however the motion was not smooth.

Future experiments for sidewinding could explore different frequencies in the waves generated by motion A, which could be useful in precise directional control. Another factor related to sidewinding that has not been explored is the impact of sheath textures, such as grooves, ridges, or stipples. An additional enhancement to the software could be additional logic to identify faulty motors that are not recoverable and adjust the sidewinding gait accordingly.

4.2.3 Tumbling

Figure 11: Transformation

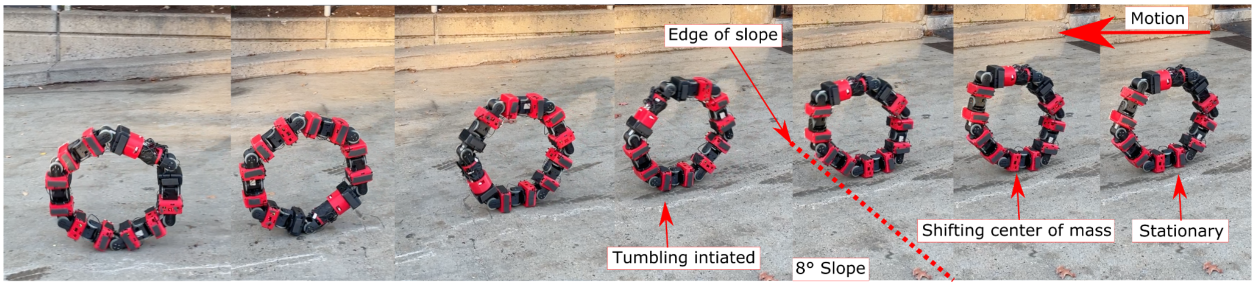

Figure 12: Tumbling

Tumbling involves two stages:

1. Change to the Hexagon configuration
2. Initiate tumbling down a sloped surface

Before the first stage was tested, a torque test was performed using half of the system. Module 0 was clamped to the table and the torque was measured as it lifted Modules 1-6. This test was done to ensure the actuators were able to lift the system without overloading. Based on the maximum torque of the actuators, the system can increase 1.5 times in mass before an overload would occur.

The first stage was then tested on a flat floor. The system was able to properly transition into the hexagon formation however in the first iteration the head and tail modules hit into each other with a significant amount of force. To mitigate this force, the transformation was split into two separate sections. The first brings the modules halfway into the configuration and then pauses for three seconds to allow for the system to settle. The head and tail are then moved together at a slower acceleration until the hexagon formation is reached. After this stage, the latching mechanism can initiate, extending the legs outwards until they hit the cavity on the tail module.

Tumbling for Stage 2 was tested outdoors on ramps found around the Northeastern Campus with inclines of 4 and 8 degrees. To test tumbling, COBRA was placed parallel to the slope such that Module 6 was on the beginning of the sloped section. The transformation to hexagon was initiated and then COBRA was tilted forward to create enough force to continue tumbling down the slope. COBRA had some trouble maintaining continuous motion on the 4 degree incline, stopping every 3-4m, however performed much better on the 8 degree incline going the full 20m length of the slope. COBRA was then tested in its full mission scenario, sidewinding to the edge of the slope, transforming into the hexagon configuration and then tumbling down the slope.

5.0 Safety Plan and Protocols Followed

Throughout the duration of the project, best practices regarding laboratory safety, emergency escape plan, and equipment were implemented as specified by our institution [22]. As it pertains to the COVID-19 Pandemic in the early stages of our project, the team complied with guidelines placed by Northeastern University and the State of Massachusetts.

6.0 Path-to-Flight

The 11 DOF multimodal sheath-covered robot with built-in joint module attachments and latch is consistent with **TRL 5** stating: "A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed." This is based on the justification that our COBRA prototype demonstrated navigation capabilities (sidewinding and tumbling) in a simulated environmental setting (angled concrete terrain and sand-covered terrain) [23]. Concept development into COBRA hardware and software through both simulation and verification testing will continue until all current funds are used.

Prior to building flight hardware, additional verification testing must be conducted to achieve **TRL 6.** Primarily, this includes sensor integration and a sensor package to read data from the payload module while surveying. The development of sophisticated exception handling logic, as well as autonomous verification of motor performance data and motor reboots, would also be essential to ensure operational environment performance can be predicted. With regard to the joint module subsystem, the module structures will need to be machined out of metal. This will increase the overall mass of the system significantly, and methods to increase the torque of the actuators may need to be implemented.

The current neoprene sheath prevents fine particulates from entering the system, however the aforementioned iris diaphragm concept will need to be implemented to properly prevent matter from entering the system during the latching transformation. As the sheath is a crucial part of COBRA's path to flight, extensive performance testing in a Dirty thermal Vacuum Chamber, bakeout, etc. would have to be performed to confirm Do-Not-Harm implications for Commercial Lunar Payload Services landers, as well as more comprehensive environmental testing. Further, space-proven fabrics such as Vectran and Kevlar would be explored as their abrasion resistance and thermal properties make them good candidates for a sheath material.

7.0 Results/Conclusions

7.1 COBRA Mini

Based on the results of the COBRA Mini testing, it can be concluded that body shape does not have a huge impact on sidewinding performance on flat ground. In order to provide more conclusive evidence, the next step would be to test sidewinding performance in porous media for each of the attachments. Further, sidewinding performance can be affected significantly by other variables other than body shape, namely friction between the system and the surface as well as amplitude, frequency and phase shift for the horizontal and vertical waves that control sidewinding. To control friction implications it's possible to add additional actuators to each module such that the coefficient of friction is controlled along the path of travel to increase the lateral motion during sidewinding and improve efficiency.

With regard to tumbling, COBRA Mini had varied success depending on the external geometry attachment used. The circular and elliptical attachments decreased stability due to the lack of contact with the flat surface. The rounded nature of those attachments meant COBRA Mini was able to tip over more easily and was only able to successfully tumble around 20% of the time. The hedgehog inspired attachment was more stable but was not very strong due to the extrusions the weight of the system rested on. This means it would not be feasible to increase in scale to the full system. The triangular prism attachment had a flat base and did not extend past the edge of the module, making it the most stable. However, with this attachment, each module only had a range of motion of +/- 60 degrees, which is not acceptable for the larger system. As a result, the square module allowed for the most support on flat surfaces while also allowing for proper range of motion.

7.2 COBRA

During the initial tumbling tests of COBRA, it was observed that tumbling slowed down when the latching modules came into contact with the ground. This is likely due to the difference in the lengths of the latching modules and the joint modules. In this case, the latching modules segment a greater length of the hexagonal configuration relative to the joint, resulting in greater surface friction when in contact with the ground. To mitigate this, a square-like geometry attachment similar to the ones placed around the joint modules will be used around the latches to achieve a more symmetrical hexagonal shape. Additionally, the joint angles will be adjusted to reflect the difference in the lengths of the modules since the joint angles were previously deduced assuming that the segments were of equal length.

Furthermore, when testing the tumbling initialization, where the hexagonal COBRA orients forward by adjusting its joint angles, we observed that while momentum is gained in the forward direction, it is not always close enough to the edge of the slope to initiate tumbling. In order to fully utilize this motion, the transformation must occur immediately prior to the start of the slope, after which gravity takes over. However, the slope must be sufficiently steep for this to happen and also depends on the contact friction between COBRA and the surface. Currently, only two modules are used to initiate tumbling, however with a closed loop system, the center of mass can be altered such that the system can roll on its own, mitigating this issue.

The steps to achieve displacement and directional control of sidewinding were difficult with both COBRA Mini and COBRA. Experimenting with Motion A and B demonstrated that B showed more consistent direction of movement, and both techniques showed a reliable change in direction through reversing the direction of a wave passing through the snake.

Based on current verification testing with both COBRA Mini and COBRA, it can be concluded that the sidewinding and tumbling mobility solutions function as designed on slopes ranging from 4 to 30.5 degrees. The system was able to perform sidewinding capabilities on both flat ground and on porous sand with minimal sinkage, indicating the ability to scale the mobility solution to regolith conditions. Further, during the tumbling testing, the system was able to utilize the gyroscopic effect for stabilization and successfully traverse steep slopes. With the integration of on board sensors and a closed loop system, stability and movement control will increase significantly. This will allow COBRA to perform obstacle avoidance on slopes to optimally traverse through its intended mission scenario.

8.0 Timeline

(orange)	To Be Completed
(yellow)	In Progress
(green)	Progress Completion

Northeastern Big Idea 2022 - COBRA Gantt Chart

TASK NAME	Duration (Weeks)	Progress Percentage
Detailed Part Design		
Module Design	6	100%
Friction Testing Setup	5	100%
Slope Testing Bed - COBRA Mini	6	100%
Sheath Design	3	100%
Head Module	15	100%
Payload Module	15	100%
COBRA Mini Design and Assembly	11	100%
Part Order		
Joint Module Materials	2	100%
Sheath Material Sample Order	2	100%
Sheath Material Full Order	1	100%
Slope Testing Bed Materials	2	100%
Batteries	2	100%
Electronics/Communications	2	100%
Fabrication and Assembly		
Payload Module	3	100%
Head Module	3	100%
Full COBRA Assembly - Mechanical	12	100%
Full COBRA Assembly - Electrical	12	100%
Angled Testing Bed Assembly	5	100%
Software		
Sidewinding Software Development	21	100%
Tumbling Software Development	15	100%
Communication	6	100%
IMU Integration	3	50%
Voltage, Current Readings	2	75%
Verification Testing		
Sheath Material Friction Testing	2	100%
Sidewinding with Analog Material	9	100%
Tumbling Transformation Tests	5	100%
Tumbling with Analog Material	10	100%
Report and Forum		
Mid Year Report	3	100%
Finalize Team Members & Register	2	100%
Book Flights, Hotel, & Other Travel	2	100%
Begin Technical Report	11	100%
Review Technical Report	2	100%
Begin Poster	4	0%
Oral Presentation Prep	4	0%

Timeline columns: Jan (24, 31), February (7, 14, 21, 28), March (7, 14, 21, 28), April (4, 11, 18, 25), May (2, 9, 16, 23, 30), June (6, 13, 20, 27), July (4, 11, 18, 25), August (1, 8, 15, 22, 29), September (5, 12, 19, 26), October (3, 10, 17, 24, 31), November (7, 14)

9.0 Budget

9.1 Total Budget

Primary Proposing University Name: Northeastern University
Project Title: COBRA: Crater Observing Bio-inspired Rolling Articulator
2022 BIG Idea Challenge

Budget Period of Performance: January 01 - December 31, 2022

Description	Rate	Phase 1 1/1/22 - 6/30/22	Rate	Phase 2 7/1/21 - 11/30/22	Proposed Budget	Total Expenditures	Remaining
A. Direct Labor - Key Personnel							
Students		23,205		30,030	53,235	53,235	-
Faculty		717		717	1,434	1,434	(0)
Subtotal Salary		***23,922***		***30,747***	***54,669***	***54,669***	(0)
Direct Labor - Other Personnel							
Subtotal Other Personnel		-		-	-	-	-
B. Fringe Benefits							
Faculty	25.50%	183	25.50%	183	366	366	-
Students	7.65%	1,775	7.65%	2,297	4,073	4,073	-
Subtotal Fringe		**1,958**		**2,480**	***4,438***	***4,438***	-
Total Labor Costs (A+B)		**25,880**		**33,227**	**59,107**	**59,107**	-
C. Direct Costs - Equipment: Fabricated		**39,285**		**5,000**	**44,285**	**14,220**	**30,065**
D. Direct Costs - Domestic Travel		-		**21,645**	**21,645**	**21,645**	-
E. Other Direct Costs							
Materials and Supplies					-	-	-
Testing Costs or Facilities Rental		-			-	-	-
Consultants		-		-	-	-	-
Services		-		-	-	-	-
Subcontracts/Subawards		-		-	-	-	-
Miscellaneous		-		-	-	-	-
Total Other Direct Costs (E)		-		-	-	-	-
F. Total Direct Costs (A+B+C+D+E+F)		**65,165**		**59,872**	**125,037**	**94,972**	**30,065**
Modified Total Direct Costs, if applicable		25,880		54,872	80,752	80,752	80,752
G.i. University Indirect Costs (Required for Phase I & Phase II)	57%	14,751	57%	31,277	46,029	46,029	46,029
G.ii. Space Grant Indirect Costs (Phase II only)			0	2,500	2,500	2,500	2,500
H. Total Direct and Indirect Costs (F+G)		**79,916.70**		**93,648.94**	**173,565.64**	**143,500.26**	**30,065.38**
% of Total Budget (Phase I should be ~46%; Phase II should be ~54%)		***46.04%***		***53.96%***			

9.2 Equipment (Fabricated)

Item	Planned Phase 1	Spent Phase 1	Planned Phase 2	New Proposed Phase 2	Spent Phase 2	Total Project Expenditures	Total Remaining Funds
Dynamixel Motors	$16,880	$9,704	$0.00	$7,196	$0	$9,704	$7,196
Dynamixel Motor Electronics	$280	$229	$0.00	$50	$0	$229	$50
Markforged Onyx Material	$1,520	$570	$0.00	$950	$0	$570	$950
Markforged Carbon Material	$1,800	$0	$0.00	$1,800	$0	$0	$1,800
Raspberry Pi	$70	$140	$0.00	$160	$66	$205	$95
Electronic Connectors	$500	$118	$0.00	$383	$0	$118	$383
Radar Electronics	$1,061	$679	$0.00	$382	$0	$679	$382
Arduino	$175	$0	$0.00	$175	$0	$0	$175
IMU	$200	$0	$0.00	$700	$0	$0	$700
Batteries	$1,500	$908	$0.00	$592	$72	$980	$520
Sheath Materials	$4,250	$228	$0.00	$4,022	$105	$333	$3,917
Mechanical Seals	$4,500	$0	$0.00	$0	$0	$0	$0
Mechanical Fasteners	$500	$393	$0.00	$107	$139	$532	-$32
Metal Stock (Shafts, Sheets and Bars)	$500	$0	$0.00	$1,000	$206	$206	$794
Machining Budget	$500	$0	$0.00	$3,000	$0	$0	$3,000
Mechanical Testing (Compliance and Friction Testing)	$750	$0	$0.00	$0	$0	$0	$0
Waterproof Testing Setup and Materials	$0	$0	$1,000.00	$0	$22	$22	$0
Verification Test Bed Materials	$1,250	$0	$0.00	$1,250	$460	$460	$790
Verification Testing Analog Materials	$550	$0	$0.00	$550	$0	$0	$550
LHS-1 Lunar Highlands Simulant (1 kg)	$0	$0	$1,050.00	$1,050	$0	$0	$1,050
Regolith Test Enclosure and Fixture	$0	$0	$300.00	$2,800	$0	$0	$2,800
Cleaning Supplies for Regolith Simulant	$0	$0	$150.00	$150	$0	$0	$150
Phase 1 Buffer for Materials and Supplies	$2,500	$0	$0.00	$2,500	$0	$0	$2,500
Phase 2 Buffer for Materials and Supplies	$0	$0	$2,500.00	$2,500	$182	$182	$2,318
Totals	**$39,285**	**$12,968**	**$5,000.00**	**$31,317**	**$1,252**	**$14,220**	**$30,066**

9.3 Stipends

Phase	Salary Type	Rate	Hours per week	Number of Weeks	Number of Students	Total Hours per Student	Total Cost
1	Student	15	7	17	13	119	$ 23,205.00
2	Student	15	7	22	13	154	$ 30,030.00
							$ 53,235.00

9.4 Travel

Item	Rate per person	# people	Total
Registration	550	13	7,150
Airfare	550	13	7,150
Lodging (4 nights)	300	13	3,900
Meals & etc. (4.5 days)	225	13	2,925
Ground Transportation	40	13	520
			$21,645

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