Final Design Review

Perforated Groove Cam Lock
Lunar Surface Operations – EVA Dust-Tolerant Handle Extension Mechanism

Team Lunar Lads

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Abstract

NASA Artemis III astronauts need a way to attach and detach various tools to an extension handle to be used during lunar EVA sample collection. Because lunar dust is so harsh and abundant, mechanisms must be designed to function regardless of the number of contact particulates. Past designs used on the Apollo missions proved to be problematic for their operators, opening the door for innovative improvement. A new mechanism has been proposed that directly addresses the performance issues of the original handle extension mentioned in NASA’s Apollo mission reports. The new mechanism boasts an open design that promotes dust tolerance while maintaining operational simplicity. The device contains two primary components: a cylindrical insert with a notched groove, and a perforated socket paired with a cam latch. The notches in the insert allow lunar dust to pass through the negative space without sacrificing contact stability. A similar effect is achieved by the perforations in the socket. The assembly meets all Neutral Buoyancy Lab (NBL) standards and is intended for use with EVA gloved hands. The approved design proposal is complete and physical development is near complete. The justification for this design pertains to the challenge specifications provided by NASA. All material requirements, as well as a finalized manufacturing plan have been identified. All specifications meet compliance, and a final prototype was tested in the NBL as well as the Simulant Lab in the Johnson Space Center.
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1 INTRODUCTION

The Micro-g NExT design challenge for the EVA Dust Tolerant Handle Extension requires that a mechanism be developed as a hand tool for astronauts exploring the lunar surface. Lunar regolith was identified as a large obstacle during EVA sampling on the Apollo era missions completed by NASA. In particular, the overwhelming presence of dust particles caused binding and jamming in the original extension tools which interfered with data collection and scientific analysis. A new tool must be developed in response to this discovery and will be tested in the NBL to simulate a lunar environment. As such, the new mechanism must meet all design specifications provided by NASA and comply with the NBL requirements.

2 DESIGN OVERVIEW

This section includes a full design description and design updates since our Critical Design Review. Full detailed drawings can be found in Appendix J, and an indented bill of materials can be found in Appendix A.

DESIGN DESCRIPTION

The subsection describes the entire system and the important individual subsystems.

System Overview

The purpose of the mechanism is to easily attach an extension handle to various hand tools, including a scoop, an auger, and a coring tool, during lunar surface extravehicular activity (EVA). The mechanism can be used in an EVA environment where mobility and visibility may be limited and tolerates the presence of abrasive lunar dust. Although the system is designed to handle a variety of tool attachments and their corresponding load cases, a scoop tool will be used for formal testing. Figure 1 shows an isometric view of the entire system, including a scoop tool, the mechanism, and the extension handle.
Material Choice

Prototypes will be made almost exclusively out of aluminum. Many of the parts are designed to be aluminum, but a recommendation may be made for steel if a future product is made. This is for ease of manufacturing, as it allows parts to be cast. Casting parts allows skipping machining many features that would be only possible or simply more expedient with the use of a four or five axis CNC mill.

The handle tubes, receiver, and cam handle are all designed to be made from aluminum. This has many advantages in that it is easy to machine, able to be welded, and has high specific stiffness. This allows parts to be more rigid by having thicker walls for the same
weight and strength. The cam handle needs to be stiff and so benefits from this material choice as well.

If the receiver is cast, it allows features such as the dust evacuation slots to be made without additional machining time or access to hardware such as a rotary table. Additionally, it easily allows the addition of more material around the hole for the bearing pin.

However, the cam and tool end may change to steel in recommendations for future models. The prototype only needs to withstand a short number of tests where an actual product may need to last much longer. For such cases, additional abrasion resistance may be necessary as wear may cause wobble or prevent full engagement. Although the tool and receiver slide past each other, only the cam face and tool end do so while under a load. This combined with the fact that the contact point of the cam is very small may lead to more pronounced wear on these surfaces. If even greater abrasion resistance is deemed necessary, a few alternatives exist to meet this need. First, aluminum may be hard anodized to increase wear resistance. Alternatively, a steel that can be heat treated for high wear resistance such as D2 or 440C may be recommended.

**Cam & Receiver**

The cam and receiver (Figure 2) are attached to the handle and house the tool-end insert. The dust relief perforations allow large amounts of dust to evacuate from the chamber, while the press-fit bushing rotates around the drill rod under a tight slip fit, preventing dust from inhibiting cam actuation.

![Figure 2. Cam & Receiver Assembly](image-url)
Cam Design and Engagement

To design a cam, it is treated as a rotating object moving past a knife edge follower. This point follower is located at a distance offset from cam, known as eccentricity. Additionally, it can be at an angle to the cam. To convert this to a profile, inversion is used in which the cam is treated as stationary, and the follower traces the cam through the desired profile. This is influenced both by the radial distance from the cam center, but also the local slope. (Zhang)

The cam was desired to be swept through a range of motion and had to accommodate a few key events. The first is that when raised fully, the tool end must be able to fit under it so that it can be removed. However, it also must protrude slightly to engage with the alignment grooves.

After, even if it has not been fully inserted, the cam needs to be able to grab the tool and slide it rearward up to the shoulder of the receiver. This is done using a steadily increasing radius. Once this point has been reached, the last phase of engagement requires a separate profile.

The final profile provides clamping to hold the tool end against the receiver. During testing, it was found that a tensile load would open the cam. Early versions used a hemispherical groove, but this contact meant that as the cam moved, friction would move the tool end forward off the shoulder, leading to device failure in tension. To fix this issue, the tool end contact was changed to an angled ramp. This led to a single, definitive contact point, allowing for more exact and predictable loading. This point can only apply a force normal to its surface. By setting this angle, it is possible to angle this vector below the pivot point. This means that any axial load pulling on the tool will provide a torque on the cam in the direction of the closed position.

The interaction between the cam and the tool-end insert is shown in Figure 5. To actuate the cam, a handle is attached to the cam itself. An ergonomic cam handle can be attached using a screw and fastener combination through the holes in the cam, as shown below in Figure 3.
Tool End

The tool end of the mechanism inserts into the receiver and interfaces with the cam. The mechanical guides help the user align the cam with the groove for easier use in low visibility situations. A hole in the groove allows for operation and dust evacuation to happen simultaneously. As shown in Figure 5, a flat contact surface was chosen for the groove to ensure that a singular contact point is maintained throughout actuation, decreasing the friction at the interface, and allowing the cam to secure the tool end insert against the mechanical stop provided by an internal shoulder on the receiver.
**Mechanism Function**

A cross-section view of the mechanism in both the closed and the open state is shown in Figure 6. In the closed position, the cam interacts with the groove at a single contact point and supports the tool-end insert in both tension and compression. In tension, the normal force acting on the cam generates a moment about the rotation point that forces the cam further closed. As the cam is closed, the tool-end insert is forced against the positive stop, supporting the mechanism in compression.
Figures 6 a) & b) show the mechanism in the open state. The nose of the cam protrudes into the mechanical guides, channeling the tool-end into the receiver in the correct orientation. When the tool-end is incorrectly aligned, the cam creates interference that prevents the part from sliding into the receiver.

Figure 6. a) Mechanism in open position b) Mechanism detail
DESIGN CHANGES SINCE CDR

Several design changes have been made since the Critical Design Review. Each change served a different purpose but contributed to improvements in sample collection and ergonomic viability. Figure 7 a) and b) provide a visual comparison of assembly improvements.

![Figure 7. a) Final assembly as described in CDR b) Updated final assembly](image)

**Actuation Handle Changes**

The design for the actuation handle has undergone several iterations prior to its definitive, final design. Originally, the handle was intended to have a large contact or “grip” area that the operator could grasp. The handle was long and slender with a relatively low profile as seen in figure 7 a). While this design promised ergonomic function with a glove, the length of the handle arm became a concern. The design was changed to a shorter handle that extended normal to the top of the cam. This limited the possibility of damaging the cam from out of plane moments caused by lateral forces. A visual demonstration of the improved resistance to unwanted bending can be seen in figure 8 below.
Cam Changes

The first change to the mechanism was a design improvement to the cam geometry. Key features, such as the contact point in a closed configuration, were left untouched. However, the method of fixing the cam to the actuation handle was altered for more reliable results in structural integrity and manufacturability. Figure 9 a) and b) demonstrate the changes in CAD models between the two iterations.

As seen in figure 8, no changes were made to the contact surfaces on the cam, but the geometry surrounding the cam attachment features was improved. In both iterations, the plan was to use threaded screws to attach an actuation handle to the cam. Originally, two blind, threaded holes were going to be drilled into the top of the cam. The concerns with this design were based on non-reliable manufacturability for blind threads, as well as a sacrifice in material strength by removing so much material. The alternative design, shown in figure 8 b) shows added material on the back of the cam with two through holes added. Two screws can be inserted and fasted by cap nuts on the opposite side, creating a floating fastener and loads the bolts in shear.
Scoop Changes

The scoop design provided in the CDR was a placeholder meant to serve as a visual representation. Since then, geometry has been fully developed modeling the original scoop designs of the apollo missions. Since the primary objective of the scoop is sample retention, a box like design was created. The bottom face of the scoop serves as the main collection feature. All other faces serve as retaining walls to limit the potential of sample loss during EVA.

![Figure 10. Scoop Change](image)

3 IMPLEMENTATION

The prototype is designed to be made from aluminum using a variety of techniques such as welding, casting, milling, and turning. A plan will allow a prototype to be assembled efficiently in terms of cost and time.

PROCUREMENT

Materials for the project can both be bought locally as well as ordered online. The drill rod and bushings used for the cam pivot will be bought from McMaster-Carr. The rest of the mechanism will be fabricated, so raw materials will need to be sourced. A detailed list of these sources can be found in Appendix F. For many of these processes, access to manufacturing equipment is required. This is available through school resources and Mustang ‘60 machine shop. Care has been taken to design parts that may be manufactured using accessible methods.

MANUFACTURING

Below is a list of steps required to make individual parts needed to assemble a working prototype.
Handle (aluminum tube)

1. Cut main tube to length using a chop saw
2. Cut cross hole for handle tube using belt sander with proper diameter
3. Cut cross tube to length
4. Deburr all edges
5. Assemble - weld the two pieces together to form handle subassembly

Cam (aluminum)

1. Waterjet rough profile out of flat stock
2. Drill and ream hole for bushing in same op to ensure perpendicularity to first face
3. Press in bushing
4. Drill two holes into cam for cam handle
5. Break all edges and deburr

Cam Handle (aluminum flat stock and tube)

1. Mill stock to size and cut slot to fit around cam
2. Drill two holes to match those in cam
3. Weld to square tubing to make a T handle
4. Break edges and deburr

Receiver (cast aluminum)

1. Print part using resin or PLA 3D printer complete with gating
2. Prepare for investment casting and make mold
3. Cast part in aluminum
4. Remove gating and excess material using band saw
5. Use a lathe to turn important features in a single operation, orient as horizontal as possible so bore is parallel to handle
6. Face front surface until it cleans up for a datum surface
7. Drill through to largest possible
8. Bore to size
9. Bore internal shoulder precisely, measuring from front of part
10. Remove and flip turn down to diameter to register into handle tube, remove from lathe
11. Clamp with V block with bore horizontal in vice
12. Locate centerline of part, move to hole location from centerline and front face
13. Center drill, drill, ream hole for pin
14. Remove from vice
15. Deburr all edges

Tool End (cast aluminum)

1. Print part using resin 3D printer complete with gating
2. Prepare for investment casting and make mold
3. Cast part in aluminum
4. Remove gating and excess material using band saw
5. Face and turn to diameter on first side
6. Drill through to size
7. Flip, face and turn to diameter
8. Cut fillet on side to engage the receiver and cam, remove from lathe
9. Deburr and break all edges

**Scoop** (aluminum sheet)
1. Measure and draw bend and cut lines onto aluminum flat stock
2. Bend into desired shape
3. Weld pieces on that cannot be bent
4. Cut a piece of round tube stock at an angle
5. Weld to scoop
6. Deburr and break all edges

**ASSEMBLY**
Below is the list of assembly operations needed to build the final prototype.

**Welding receiver to handle**
1. Align slot of receiver perpendicular to the cross handle
2. Weld together

**Fit cam and receiver to tool end**
1. Sand cam face
2. Repeatedly test with receiver to achieve as tight as fit as possible
3. Press in pin once fit is achieved

**Attach scoop tool to tool end**
1. Ensure tube on end of scoop tool is free of weld seam
2. Press fit tube onto tool end
3. Align engagement slot perpendicular to scoop tool
4. Weld the two together

**Attach cam handle to cam**
1. Attach cam handle to cam using socket head cap screws

**4 DESIGN VERIFICATION**
Due to the nature of the design challenge, strict specifications have been provided. To maintain eligibility, all specifications must be met prior to final prototype shipping in May.
To ensure that these specifications are met, structured testing has been assigned to each specification. To complete the testing, a measuring tape, balance, weights, and a force gauge are required.

**SPECIFICATIONS**

Many of the specifications from the design challenge are easily measured or verified simply by inspection. However, some are more ambiguous or subjective. Of these, function after burial, function with gloved hands, and the measurement of actuation force proved to be the most complicated to test. A list of these tests and requirements to be met are provided in Table 1 and Table 2.
### Table 1. NASA Specifications

<table>
<thead>
<tr>
<th>No.</th>
<th>Requirement</th>
<th>Status</th>
<th>Explanation if Applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>An extension handle with integrated tool attachment mechanism; a scoop tool to attach to the mechanism; and a second, standalone tool attachment mechanism shall be produced.</td>
<td>Complies</td>
<td>Manufacturing resources are available to meet this requirement</td>
</tr>
<tr>
<td>2</td>
<td>If the mechanism design includes a receptacle for a mating part, place the receptacle end on the extension handle.</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Torque required to actuate the tool attachment mechanism shall not exceed 30 in-lb. (3.4 Nm)</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Extension handle, mechanism, and scoop shall maintain structural integrity when interfaced together and used to scoop soil samples.</td>
<td>Complies</td>
<td>Lunar regolith testing necessary to verify mechanical design</td>
</tr>
<tr>
<td>5</td>
<td>The tool attachment mechanism shall restrain the scoop tool and eliminate wobbling of the tool.</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>The tool attachment mechanism shall be dust-tolerant and remain operable after burial in lunar regolith simulant.</td>
<td>Complies</td>
<td>Prototype testing was conducted in sand, will also be tested in regolith simulant</td>
</tr>
<tr>
<td>7</td>
<td>The proposed design shall specify all materials the provided hardware will be made from.</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>The extension handle and non-interfacing part of the scoop may be plastic or 3D printed out of NBL-accepted materials. A waiver may be granted on a case-by-case basis.</td>
<td>Complies</td>
<td>Materials are specified in the BOM provided</td>
</tr>
<tr>
<td></td>
<td><em>(No regular PLA. Tough PLA is okay.)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>All components of the tool attachment mechanism and the interfacing part of the scoop shall be made of metal.*</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>The total length of the extension handle with mechanism shall be 28-32 inches, not including the scoop.</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>The total weight of the extension, handle, and mechanism (not including scoop tool) shall be less than 5 lbs.</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>The length of the scoop should be 13-16 inches.</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>The weight of the scoop should be less than 3 lbs.</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>The tool attachment mechanism must be operable with EVA gloved hands (like heavy ski gloves).</td>
<td>Complies</td>
<td>Tested with a welding glove</td>
</tr>
<tr>
<td>15</td>
<td>The extension handle, tool attachment mechanism, and scoop tool shall use only manual power.</td>
<td>Complies</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>There shall be no holes or openings which would allow/cause entrapment of fingers on the device.</td>
<td>Complies</td>
<td>Prototype testing will be conducted to confirm compliance</td>
</tr>
<tr>
<td>17</td>
<td>There shall be no sharp edges on the device.</td>
<td>Complies</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. General Specification Table

<table>
<thead>
<tr>
<th>Spec. #</th>
<th>Requirement or Target</th>
<th>Tolerance</th>
<th>Risk*</th>
<th>Compliance**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Actuation Force</td>
<td>20 lbf</td>
<td>Max</td>
<td>T</td>
</tr>
<tr>
<td>2</td>
<td>Actuation Torque</td>
<td>30 in-lbf</td>
<td>Max</td>
<td>T</td>
</tr>
<tr>
<td>3</td>
<td>No Yielding of Components</td>
<td>1.2</td>
<td>Safety Factor</td>
<td>L</td>
</tr>
<tr>
<td>4</td>
<td>Axial, Torsional, Bending, Resistance; Deflection</td>
<td>[0.050°/ 10 lbf]</td>
<td>Max</td>
<td>M</td>
</tr>
<tr>
<td>5</td>
<td>Dust Test Survey</td>
<td>4</td>
<td>Out of 5</td>
<td>M</td>
</tr>
<tr>
<td>6</td>
<td>Material Choice</td>
<td>Metal</td>
<td>Pass/Fail</td>
<td>L</td>
</tr>
<tr>
<td>7</td>
<td>Overall Length</td>
<td>30 in</td>
<td>± 2 in</td>
<td>L</td>
</tr>
<tr>
<td>8</td>
<td>Mechanism and Handle Weight</td>
<td>3 lbf</td>
<td>Max</td>
<td>L</td>
</tr>
<tr>
<td>9</td>
<td>Scoop Length</td>
<td>14.5 in</td>
<td>± 1.5 in</td>
<td>L</td>
</tr>
<tr>
<td>10</td>
<td>Scoop Weight</td>
<td>3 lbf</td>
<td>Max</td>
<td>L</td>
</tr>
<tr>
<td>11</td>
<td>Usability Survey</td>
<td>4</td>
<td>Out of 5</td>
<td>M</td>
</tr>
<tr>
<td>12</td>
<td>Edge Radius</td>
<td>1/8 in</td>
<td>Min</td>
<td>L</td>
</tr>
</tbody>
</table>

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
** Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test

TESTING AND RESULTS

Prior to the completion of final assembly verification, two metal prototypes were shipped to Houston for further testing. Subsequent tests were completed using a verification prototype.

The verification prototype testing was meant to fulfill the test procedures included in the DVPR (Appendix D). In the absence of the cast aluminum receiver and tool-end parts, the verification prototype mechanism was 3D-printed with PLA and fit with an aluminum cam, bushing, and drill rod. Because of the different mechanical properties of PLA, some verification prototype testing does not correspond to the metal prototypes.

The metal prototypes were tested onsite at NASA’s Neutral Buoyance Lab and Johnson Space Center’s Lunar Simulant Lab in Houston, Texas during NASA Micro-g NExT Testing Week. The results of these tests are more representative of the mechanism’s performance. A different set of test procedures was used for these tests, as they were conducted separately from the DVPR.

Verification Prototype Testing

Most of the planned verification tests were completed through inspection. The overall dimensions and weight requirements of the assembly were checked with metrology devices in Cal Poly machine shops. All measurements complied with specifications provided by the Micro-g NExT staff. Ergonomics and mechanism yield were tested by simulating the NBL operations plan in a dry environment. The mechanism, although constructed from PLA, functioned as intended and withstood all loads associated with sample collection. A more in-depth review of the ergonomic performance of the device can be found in the Micro-g NExT Test Week section.

Actuation force testing was modified to reflect use with an aluminum assembly, rather than measure the force in dry conditions with PLA parts. Testing procedures were altered to reflect this change, with data collection consisting of user feedback obtained during
test week at the Johnson Space Center. This data can be found in the Micro-g NExT Test Week section.

Similar to actuation force, deflection tests were altered to conform with user feedback. Data collection was based on a numerical scale that reflected how much movement a user could detect of the tool end relative to the extension shaft. Initial tests with the verification prototype proved successful. The test subject reported a 5, indicating that no movement was detected, and the device appeared to be rigid. The test was later repeated in the Neutral Buoyancy Lab.

Dust tolerance was initially tested in a dry environment with the verification prototype. The mechanism was buried in both an open and closed configuration. Once the device was submerged, system functionality was reassessed. Data collection was based on verbal feedback using the same scale as the NBL test operations. Preliminary feedback indicated that the device worked with a reasonable amount of dust removal from the user. A demonstration of a burial test can be found in figure 11.

![Figure 11. Verification prototype burial test](image)

Sharp edges were checked by inspection after all parts were deburred, sanded, sand blasted, and buffed. Prior to shipping, it was determined that all hazards were removed, and the device was ready to be tested in the NBL.

**NASA Micro-g NExT Test Week**

The testing conducted in the Neutral Buoyancy Lab (NBL) was an underwater test in which a NASA astronaut test diver conducted test procedures (Appendix F) in a micro-gravity, lunar surface simulant setting with EVA gloves. Instructions were verbally communicated to the diver step by step, and verbal feedback (on a 1-5 scale) was returned.
**Figure 12.** Team members in NBL test control room communicating with NBL diver during underwater testing

**Figure 13.** NBL Test Diver conducting underwater test procedures on the assembly
Verbal feedback to a set of prompts at the end of each test procedure was provided by the diver and is shown in table 3.

**Table 3. Underwater Test Results (Verbal)**

<table>
<thead>
<tr>
<th>Test</th>
<th>Prompt</th>
<th>Score (1-5)</th>
<th>Comments from test diver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Disengagement</td>
<td>How easy it was to actuate the mechanism?</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>How easy it was to separate the tool from the receiver?</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>How easy it was to keep the tool secure during disengagement?</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Device Engagement</td>
<td>How easy it was to inset the scoop into the mechanism?</td>
<td>5</td>
<td>No issues, easy, no force, no pinch</td>
</tr>
<tr>
<td></td>
<td>How easy it was to close the actuation handle?</td>
<td>5</td>
<td>No problems whatsoever</td>
</tr>
<tr>
<td></td>
<td>How easy it was to keep the tool secure during engagement?</td>
<td>5</td>
<td>Good diameter handle, no issue putting it together</td>
</tr>
<tr>
<td>Tensile &amp; Compression Control</td>
<td>How stable did the mechanism feel during plunging operation?</td>
<td>5</td>
<td>No movement, flex, or rotation on the tool</td>
</tr>
<tr>
<td></td>
<td>How easy was it to operate the tool?</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Torsion Control</td>
<td>How stable did the mechanism feel during operation?</td>
<td>4</td>
<td>Tiny bit of flex on rotation – not an actual problem</td>
</tr>
<tr>
<td></td>
<td>How difficult did it feel to rotate the tool?</td>
<td>3</td>
<td>Neutral</td>
</tr>
<tr>
<td>Regolith Retrieval</td>
<td>How easy was it to obtain a sample?</td>
<td>3</td>
<td>Overall length made it hard to squat</td>
</tr>
<tr>
<td>Drop Test</td>
<td>How easy was it to insert the scoop into the mechanism?</td>
<td>5</td>
<td>No problem putting it back in</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------------</td>
<td>---</td>
<td>-------------------------------</td>
</tr>
</tbody>
</table>

Dry testing was conducted in lunar simulant lab at the Johnson Space Center using lunar simulant BP-1. Figure 14 shows the standalone mechanism during testing. The mechanism was tested with the groove full of regolith simulant.

![Standalone mechanism during dry testing](image)

**Figure 14.** Standalone mechanism during dry testing

All test results from the dry testing were subjective and verbally communicated. Engineers from NASA’s EVA tools team tested the mechanism by repeatedly burying it in regolith and engaging the mechanism.

General takeaways from NASA EVA Tool Engineers after dry testing:

- Even with the groove completely full of regolith, the mechanism still securely engaged
  - “Works really well”
- Dust removal was very effective
  - Any dust inside the groove was forced through the slot and out of the mechanism
- Alignment guides were effective and helpful
- Add a larger chamfer to the tool-end
- A secondary latch to keep the cam in place should be added to support 2-fault engineering

## 5 DISCUSSION & RECOMMENDATIONS

The verification prototype tests, the underwater lunar surface tests, and the dry lunar simulant tests displayed the strengths and weaknesses of the mechanism’s design. Test results and design recommendations provide key takeaways from this project and can help advise future design iterations.
One of the main weaknesses of the mechanism was its reliance on friction. Once the cam is engaged, rotational friction helps it stay in place. As the mechanism underwent a high number of usage cycles, the interference between the cam and the receiver decreased, reducing the amount of friction acting on the cam and limiting the lifespan of the mechanism. Material selection, changes in geometry and tolerances, or a secondary lock could all contribute to a more successful version of this mechanism.

Using steel, or a harder metal, for the interaction between the cam, receiver, and tool-end would cause the mechanism to wear down at a slower rate, improving the mechanism’s reliability and lifespan. It has the advantage that it can be ground, allowing higher precision to be achieved. If hardened, it would be able to sustain higher elastic deformation due to higher contact stresses than both aluminum and softer steels. Considerations regarding weight, manufacturing, and assembly would need to be made to be able to combine steel and aluminum parts.

Discussion with NASA engineers working in EVA tool development as well as an experienced astronaut highlighted the importance of designing for failure. All tools related to space travel must function at multiple tiers of failure. For example, EVA suit visors have multiple layers so that the user will survive if one layer is fractured. During testing in the NBL, the diver unintentionally knocked the actuation handle to the open position, causing mechanism failure from unexpected separation. Future iterations of this design would benefit from a secondary mechanism that keeps the cam locked in a closed position. The usage of a secondary lock is standard procedure for any mechanism that will be on the International Space Station. If incorporated into this design, unintentional device disengagement would be prevented, whether it be from user error or repeated axial loads.

One detectable operating difficulty during dry testing was caused by part irregularities from manufacturing. It was discovered that imperfections on the tool end caused an interference between the mechanical guides and the nose of the cam. This unintended interference led to binding but could be remedied by more precise manufacturing processes. It is recommended to machine the tool end and receiver in a CNC mill to allow for more repeatable results.

The mechanical alignment guides were effective in aligning the cam with the groove, even in low visibility settings. In the current configuration, the mechanical guides directly interact with the cam, taking away from the flat contact surface inside the groove. Placing the mechanical guides on the side of the tool-end insert to interact with pins on the inside of the receiver would increase the possible contact area for the cam, making the design more reliable.

6 CONCLUSION

The goal of this project was to re-design the existing extension handle mechanism by addressing dust tolerance issues while keeping EVA ergonomics, safety, and mechanism function in consideration throughout the design process. Initial designs were submitted to NASA’s Micro-g NExT design challenge and approved to move into Phase II, culminating with test week at NASA’s Johnson Space Center. The final design was successful in
meeting all of its design requirements while utilizing a unique approach to functioning on the lunar surface. The metal prototypes were successful in all rounds of testing at the Johnson Space Center and received positive reviews from both NASA EVA tools engineers and the test diver. With future improvements, the design could not only meet the requirements as laid out but excel for the specified task.
APPENDICES

APPENDIX A – USER MANUAL

Instructions to operate the mechanism:

1. Start with the mechanism disassembled and the cam disengaged
2. With the tool-end in one hand and the extension handle in the other, align the mechanical guides on the tool end with the cam surface
3. Insert the tool-end into the receiver completely (contacts back surface of the receiver chamber)
4. Engage the cam by rotating the handle into the closed position

Device Disengagement

1) Place assembly in vertical upright position
2) Rotate cam handle to the open position
3) Place dominant hand on extension handle shaft
4) Place non-dominant hand on the tool side
5) Pull mechanism apart
   a. User will note mechanism response and assess ease of disengagement
6) User will provide verbal feedback and rate the ease of disengagement on a scale of 1-5

Device Engagement

1) Start with the mechanism disassembled and the cam disengaged
2) Grasp tool-end with non-dominant hand
3) Grasp extension handle in dominant hand
4) Align parts concentrically and insert tool-end
5) Use the mechanical guides to align tool-end groove with the cam surface
6) Push tool-end into contact with back stop
7) Engage the cam by rotating the handle into the closed position
   a. User will note mechanism response and assess ease of engagement
8) User will provide verbal feedback and rate the ease of engagement on a scale of 1-5

Sample Collection

Tensile and Compression Control

1) Place one hand on each shaft handle
2) Plunge scoop tool into regolith by applying coaxial force to extension shaft
3) Remove scoop tool from regolith by pulling up in the opposite direction of insertion
4) Repeat motion in new location
5) User will provide verbal feedback and rate the ease of operation on a scale of 1-5
6) User will provide verbal feedback on mechanism stability on a scale of 1-5
Torsion Control

1) Place one hand on each shaft handle
2) Plunge scoop tool into regolith
3) Rotate counterclockwise
   a. User will note scoop tool response and assess apparent rigidity
4) Repeat rotation in clockwise motion
   a. User will note scoop tool response and assess apparent rigidity
5) User will provide verbal feedback on ease of operation on a scale of 1-5
6) User will provide verbal feedback on mechanism stability on a scale of 1-5

Regolith Retrieval

1) Place one hand on each shaft handle
2) Plunge scoop tool into regolith
3) Relocate non-dominant hand to the center of the shaft handle
4) Position dominant hand on the extension shaft
5) Scoop regolith by using a shoveling motion, bringing the scoop head to an upright position
   a. User will note assembly response, assessing apparent rigidity and amount of regolith retained
6) Discard regolith
7) User will provide verbal feedback and rate ease of use on a scale of 1-5
8) User will provide verbal feedback and rate sample retention on a scale of 1-5

Assembly After Burial

1) Before disassembly, use the scoop tool to dig a 2-3” deep trench to bury the full assembly
   a. The trench must be deep and wide enough to completely submerge the mechanism subassembly in lunar regolith simulant. It is acceptable if parts of the scoop tool and/or extension handle are not submerged
2) Disassemble the mechanism by rotating the cam handle 90 degrees and removing the tool-end insert from the receiver
3) Place the parts in the trench. The tool-end side of the mechanism should not be touching the receiver.
4) Cover the mechanism in lunar regolith. The entire mechanism should be covered in regolith simulant
5) Remove the extension handle from the regolith with one hand and the scoop tool with the other hand
6) Allow large amounts of regolith to drain from each part
7) Orient the mechanical guides on the tool-end to line up with the cam surface
8) With the cam handle disengaged, insert the tool-end into the receiver
9) Actuate the cam until it has reached the fully-closed position, or ample physical resistance is met
10) Verbally communicate the state of the cam after actuation using one of three descriptions:
a. Fully engaged (Cam completely closed and the mechanism is secure)
b. Partially engaged (Cam can close partly, but not all the way. Mechanism may be wobbly)
c. Unable to engage (Cam will not partially close. The tool-end cannot be attached to the receiver).
## APPENDIX B – RISK ASSESSMENT

<table>
<thead>
<tr>
<th>Risk</th>
<th>Risk #</th>
<th>Consequence Category</th>
<th>Likelihood x Consequence Score</th>
<th>Controls</th>
<th>Revised Likelihood x Consequence Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger Entrapment</td>
<td>1</td>
<td>Human Safety</td>
<td>2x1</td>
<td>Marked with tape</td>
<td>1x1</td>
</tr>
<tr>
<td>Suit Puncture</td>
<td>2</td>
<td>Human Safety</td>
<td>1x5</td>
<td>Marked with tape; Rounded edges</td>
<td>1x4</td>
</tr>
<tr>
<td>Hand Fatigue</td>
<td>3</td>
<td>Performance</td>
<td>2x2</td>
<td>Designed for minimal force needed</td>
<td>2x2</td>
</tr>
<tr>
<td>Mechanical Failure</td>
<td>4</td>
<td>Asset</td>
<td>1x4</td>
<td>Analysis and testing</td>
<td>1x4</td>
</tr>
</tbody>
</table>
### Risk Matrix

<table>
<thead>
<tr>
<th>CONSEQUENCE</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>Minimal consequence to objectives/goals</td>
<td>Minor consequence to objectives/goals</td>
<td>Unable to achieve a particular objective/goal, but remaining objective goals represent better than minimum success or outcome</td>
<td>Unable to achieve multiple objectives/goals but minimum success can still be achieved or claimed</td>
<td>Unable to achieve objectives/goals such that minimum success cannot be achieved or claimed</td>
</tr>
<tr>
<td>Safety Human</td>
<td>Discomfort or nuisance</td>
<td>First aid event per OSHA criteria</td>
<td>No lost time injury or illness per OSHA criteria</td>
<td>Lost time injury or illness per OSHA criteria</td>
<td>Loss of life</td>
</tr>
<tr>
<td>Asset</td>
<td>Minimal consequence: asset has no sign of physical damage</td>
<td>Minor consequence: asset has cosmetic damage and is repairable</td>
<td>Minor consequence: asset is damaged but repairable</td>
<td>Major consequence: asset is substantially damaged but repairable</td>
<td>Destroyed: asset is compromised, and un-repairable: a total loss</td>
</tr>
<tr>
<td>Schedule</td>
<td>Minimal consequence</td>
<td>Critical path is not slipped; total slack of slipped tasks will not impact critical path in less than 10 days</td>
<td>Critical path is not slipped; total slack of slipped tasks is within 10 days of impacting the critical path</td>
<td>Critical path slips</td>
<td>Critical path slips and one or more critical milestones or events cannot be met</td>
</tr>
<tr>
<td>Cost</td>
<td>Minimal consequence</td>
<td>Minor cost consequence: Cost variance $\leq$ 5% of total approved FY baseline</td>
<td>Cost consequence: Cost variance $&gt; 5%$ but $\leq 10%$ of total approved FY baseline</td>
<td>Cost consequence: Cost variance $&gt; 10%$ but $\leq 15%$ of total approved FY baseline</td>
<td>Major cost consequence: Cost variance $&gt; 15%$ of total approved FY baseline</td>
</tr>
</tbody>
</table>
Design Hazard Checklist:

☑

Team: F15 - LUNAR LADS

Faculty Coach: DR. SCHUSTER

Y  N
☑  ☐  1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☑  ☐  2. Can any part of the design undergo high accelerations/decelerations?
☐  ☑  3. Will the system have any large moving masses or large forces?
☐  ☑  4. Will the system produce a projectile?
☐  ☑  5. Would it be possible for the system to fall under gravity creating injury?
☐  ☑  6. Will a user be exposed to overhanging weights as part of the design?
☐  ☑  7. Will the system have any sharp edges?
☐  ☑  8. Will you have any non-grounded electrical systems?
☐  ☑  9. Will there be any large batteries or electrical voltage (above 40 V) in the system?
☐  ☑  10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐  ☑  11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐  ☑  12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐  ☑  13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐  ☑  14. Could the system generate high levels of noise?
☑  ☐  15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc.?
☑  ☐  16. Is it possible for the system to be used in an unsafe manner?
☐  ☐  17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any “Y” responses, complete a row in your Design Hazard Plan including (a) a description of the hazard, (b) a list of corrective actions to be taken, and (c) the date you plan to complete the actions.
### APPENDIX C – FINAL PROJECT BUDGET

<table>
<thead>
<tr>
<th>Item</th>
<th>Qty</th>
<th>Part. Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Flat Stock</td>
<td>1</td>
<td>$17.86</td>
<td>$17.86</td>
</tr>
<tr>
<td>440C SST Tube Stock</td>
<td>1</td>
<td>$56.17</td>
<td>$56.17</td>
</tr>
<tr>
<td>Press-Fit Drill Bushing (McMaster-Carr 96511A366)</td>
<td>8</td>
<td>$12.21</td>
<td>$97.68</td>
</tr>
<tr>
<td>Tight Tolerance Drill Rod (3ft) (McMaster-Carr 8893K131)</td>
<td>2</td>
<td>$3.11</td>
<td>$6.22</td>
</tr>
<tr>
<td>8-32 Screws</td>
<td>1</td>
<td>$8.03</td>
<td>$8.03</td>
</tr>
<tr>
<td>8-32 Hex Nuts</td>
<td>1</td>
<td>$1.92</td>
<td>$1.92</td>
</tr>
<tr>
<td>0.0985 Reamer</td>
<td>1</td>
<td>$22.12</td>
<td>$22.12</td>
</tr>
<tr>
<td>Shipping</td>
<td>4</td>
<td>$24.00</td>
<td>$96.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$306.00</strong></td>
</tr>
</tbody>
</table>

**Manufacturing Costs**

Provided by the school

<table>
<thead>
<tr>
<th>Travel</th>
<th>Qty</th>
<th>Part. Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round trip airfare to Houston</td>
<td>5</td>
<td>$597.93</td>
<td>$2,989.65</td>
</tr>
<tr>
<td>Hotel</td>
<td>1</td>
<td>$1,712.88</td>
<td>$1,712.88</td>
</tr>
<tr>
<td>Transport</td>
<td>1</td>
<td>$250.00</td>
<td>$250.00</td>
</tr>
<tr>
<td>Food</td>
<td>4</td>
<td>$225.00</td>
<td>$900.00</td>
</tr>
<tr>
<td><strong>Total Travel</strong></td>
<td></td>
<td></td>
<td><strong>$5,852.53</strong></td>
</tr>
</tbody>
</table>

* $1000 allocated by Cal Poly ME Senior Project Budget cannot be applied to travel to Texas

** $2500 awarded by CA Space Grant can be used for travel. $1200 provided by NASA Micro-g NEXT (all went to hotel)
## APPENDIX D – DESIGN VERIFICATION PLAN & REPORT (DVPR)

### DVP&R - Design Verification Plan (& Report)

<table>
<thead>
<tr>
<th>Test #</th>
<th>Specification</th>
<th>Test Description</th>
<th>Measurements</th>
<th>Acceptance Criteria</th>
<th>Required Facilities/Equipment</th>
<th>Parts Needed</th>
<th>Responsibility</th>
<th>TIMING</th>
<th>TEST RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mech Force</td>
<td>Actuate mechanism with force gauge</td>
<td>Force</td>
<td>&lt;20 lbf</td>
<td>Force Guage</td>
<td>Final Mechanism</td>
<td>Matt</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Mech Torque</td>
<td>Actuate mechanism with force gauge and measure length of mechanism arm</td>
<td>Force and length</td>
<td>&lt;30 in-lbf</td>
<td>Force Guage, Measuring Tape</td>
<td>Final Mechanism</td>
<td>Matt</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Mech Yield</td>
<td>During testing, mechanism does not yield</td>
<td>Yielding</td>
<td>Pass/Fail</td>
<td>N/A</td>
<td>Final Mechanism</td>
<td>Matt</td>
<td>5/9/2023</td>
<td>6/1/2023</td>
</tr>
<tr>
<td>4</td>
<td>Mech Deflection</td>
<td>Measure length between end of tool side and end of cam reciever, load tool with 10 lb weight with mechanism vertical, measure lengths again</td>
<td>Deflection</td>
<td>&lt;0.050”/10 lbf</td>
<td>10 lbf weight, Measuring Tape</td>
<td>Final Mechanism</td>
<td>Sam</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Mech Deflection</td>
<td>Make a mark on tool side and cam reciever at the same point, load the edge of the tool horizontally with 10 lb to induce a moment, measure distance between marks</td>
<td>Deflection</td>
<td>&lt;0.050”/10 lbf</td>
<td>10 lbf weight, Measuring Tape</td>
<td>Final Mechanism</td>
<td>Sam</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Mech Deflection</td>
<td>Make a mark on tool side and cam reciever at the same point, load the end of the tool horizontally with 10 lb to induce a moment, measure distance between marks</td>
<td>Deflection</td>
<td>&lt;0.050”/10 lbf</td>
<td>10 lbf weight, Measuring Tape</td>
<td>Final Mechanism</td>
<td>Sam</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Dust-Tolerant</td>
<td>Bury mechanism in lunar simulant and then have users take a usability survey</td>
<td>Usability</td>
<td>4/5 in Survey</td>
<td>N/A</td>
<td>Final Mechanism</td>
<td>Andrew</td>
<td>5/9/2023</td>
<td>6/1/2023</td>
</tr>
<tr>
<td>8</td>
<td>Handle and Mech Weight</td>
<td>Weigh the handle and the mechanism</td>
<td>Inspection</td>
<td>30 ± 2 in</td>
<td>Measuring Tape</td>
<td>Final Assembly</td>
<td>Andrew</td>
<td>5/9/2023</td>
<td>5/16/2023</td>
</tr>
<tr>
<td>9</td>
<td>Scoop Length</td>
<td>Measure the length of the scoop</td>
<td>Inspection</td>
<td>14.5 ± 1.5 in</td>
<td>Measuring Tape</td>
<td>Scoop</td>
<td>Dylan</td>
<td>5/9/2023</td>
<td>5/15/2023</td>
</tr>
<tr>
<td>10</td>
<td>Scoop Weight</td>
<td>Measure the scoop</td>
<td>Inspection</td>
<td>&lt;3 lbf</td>
<td>Balance</td>
<td>Scoop</td>
<td>Dylan</td>
<td>3/10/2023</td>
<td>3/10/2023</td>
</tr>
<tr>
<td>11</td>
<td>Usability</td>
<td>Have users take a usability survey</td>
<td>Usability</td>
<td>4/5 in Survey</td>
<td>N/A</td>
<td>Final Assembly</td>
<td>Andrew</td>
<td>5/9/2023</td>
<td>6/1/2023</td>
</tr>
<tr>
<td>12</td>
<td>Sharp Edges</td>
<td>Inspect that there are no sharp edges</td>
<td>Inspection</td>
<td>&gt;1/8 in</td>
<td>N/A</td>
<td>Final Assembly</td>
<td>Matt</td>
<td>5/9/2023</td>
<td>5/16/2023</td>
</tr>
</tbody>
</table>
APPENDIX E – DVPR TEST PROCEDURES

Design specifications provided by NASA are outlined in Appendix J. The compliance status of each specification will be updated through testing and analysis. All tests and their corresponding specifications can be found in Appendix G.

Actuation Force

Compliance with the specification of a maximum actuation torque of 30 inch-pounds will be verified using a force gauge to calculate the torque required to move the cam to the open position. The standalone mechanism will be oriented in a fixed position and placed in a moving cart. One end of a tensile force gauge will be attached to the cam handle at a fixed height measured from the top of the receiver mechanism, while the other is fixed to an anchor on a wall normal to the cart path of the mechanism. The layout of the testing apparatus can be seen in figure __.

Figure 7. Schematic of actuation torque test apparatus

To acquire data, the cart will be pulled away from the wall to impart an actuation force perpendicular to the cam handle. The cart’s motion will be restricted to the horizontal axis to prevent out of plane forces from acting on the handle. When the cam starts to disengage, the force gauge reading will be recorded, and torque will be calculated using the measured contact height on the handle. To reduce measurement error, this experiment will be repeated several times and the average actuation torque will be recorded and compared with the specifications in Appendix G.

This experiment has not yet been conducted, and therefore no data has been collected. With reasonable certainty, it can be predicted that the mechanism will meet the specification due to design features. The frictional area at the contact point between the walls of the receiver and cam has been minimized. Initial use of an aluminum prototype proved that the actuation torque is low, but it has not been measured.
**Structural Integrity**

Micro-g staff have not provided expected load cases for tool use. Assumed load cases were used to conduct all numerical mechanical analyses.

Assumed load cases:

- 30 in-lbf torque applied to cam lever during actuation (specified maximum)
- 60 lbf normal force between cam and groove at the closed contact point
- 60 in-lbf torque applied to extension handle
- 6 lbf at 48 in. overall length (specified maximum length)
- 60 lbf radial contact force on bushing and drill rod (bearing load)

Appendix C details the mechanical analysis calculations conducted to find the estimated factors of safety as shown in Table 2.

For each component, loads were applied as described, the stress was calculated, and converted to uniaxial stress. This value was compared to the yield value for that material to calculate the factor of safety.

**Table 2.** Calculated factors of safety for components under each load case

<table>
<thead>
<tr>
<th>Factors of Safety</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing- Drill Rod</td>
<td>21.2</td>
</tr>
<tr>
<td>Bearing- Bushing</td>
<td>21.2</td>
</tr>
<tr>
<td>Handle Bending</td>
<td>47.7</td>
</tr>
<tr>
<td>Pin Tearout</td>
<td>33.3</td>
</tr>
<tr>
<td>Pin Shear</td>
<td>6.0</td>
</tr>
<tr>
<td>Torsion - Tube</td>
<td>170.0</td>
</tr>
<tr>
<td>Torsion - Cam</td>
<td>57.7</td>
</tr>
</tbody>
</table>

The high factors of safety indicate that the assembly will maintain structural integrity under any applied loads less than or equal to the assumed load cases. The very high factors of safety allow for higher loads that may be applied. Engineering judgement was used in order to determine these load cases; however the ambiguity dictates that the higher factors of safety are needed in order to be certain the mechanism does not yield during testing.
Weight

To comply with the maximum weight specification hollow features, lightweight materials, and perforations are used where possible. The high specific strength of aluminum allows the design to be optimized for both stiffness and weight. The current design weighs in at 2.9 pounds for the handle and mechanism. To validate this design specification, mass property evaluation was conducted on the assembly. The mechanism was weighed in order to validate this criteria has been met.

EVA Glove Operation

A crucial design specification is that the mechanism must be operable with EVA gloves. Due to feedback from both NASA engineers and Cal Poly faculty, tool alignment guides have been added to aid mechanism engagement in limited visibility scenarios such as EVA operation. A redesign was carried out to minimize protrusion and snag hazards while promoting ease of use.

In order to simulate EVA gloved operation, we will use a combination of gloves simultaneously. A close-fitting glove will be worn first. A hockey glove will then be worn over this first glove. Together, this combination will limit tactile feedback and dexterity as well as the range of motion. To evaluate ease of use, a user survey will rate aspects of use on a scale of 1 to 5. Similar to this preliminary testing, a survey will be used for the NBL divers to evaluate their experiences.

Dust Tolerance

Performance of the mechanism in relation to dust tolerance will be assessed using dry tests prior to the shipping date. The device will be buried in lunar simulant in two orientations: a disengaged mechanism and an engaged mechanism. For the disengaged mechanism test, the tool-end and receiver will be buried separately. After burial, the parts will be retrieved, and the user will re-engage the mechanism. Verbal feedback will then be collected, rating the performance of the mechanism as well as ease of use on a scale of 1 to 5. This process will be repeated with the mechanism engaged, and the same feedback will be collected.

This experiment has not been conducted as of April 18th, 2023. However, it is likely that the results will be acceptable considering the design features described in section 2.1.

Assembly Dimensions

Size specifications for the final assembly can be found in Appendix J. To verify that the device is compliant with these requirements, measurements of key dimensions will be acquired prior to shipment. Each test is identified in the DVP table in Appendix G.
APPENDIX F – NASA MICRO-G NEXT TEST PROCEDURES & SCRIPT

Instructions to operate the mechanism:

1. Start with the mechanism disassembled and the cam disengaged
2. With the tool-end in one hand and the extension handle in the other, align the indicating marks on the tool end with the actuation handle
3. Insert the tool-end into the receiver completely (contacts back surface of the receiver chamber)
4. Engage the cam by rotating the actuation handle into the closed position

Device Disengagement

1. Place dominant hand on the extension handle shaft, in between the marked lines
2. Place non-dominant hand on tool side shaft
3. Orient assembly into horizontal position, away from your body
4. Place non-dominant hand on actuation handle
5. Rotate actuation handle to open position

On a scale of 1 to 5, (1 meaning too much force and 5 meaning very little force), how easy was to open the actuation handle?

6. Place non-dominant hand on the tool side
7. Pull mechanism apart

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it to separate the scoop from the mechanism?

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it to keep the tool secure in your hands while disengaging?

Device Engagement

1. Start with the mechanism disassembled and the actuation handle disengaged
2. Grasp tool-end with non-dominant hand
3. Grasp extension handle in dominant hand in between the indicating lines
4. Align parts concentrically using the indicating lines as a reference and insert tool-end
5. Push tool-end into contact with back stop

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it to insert the scoop into the mechanism?

6. Orient the assembly to the vertical position, scoop side up
7. Engage the cam by rotating the actuation handle into the closed position using non-dominant hand
8. Re-orient assembly back to horizontal position
On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it to close the actuation handle?

9. User will provide verbal feedback and rate the ease of engagement on a scale of 1-5

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it to keep the tool secure in your hands while engaging the mechanism?

**Tensile and Compression Control**

1. Place one hand on each extension shaft handle
2. Lightly plunge scoop tool into regolith by applying coaxial force to extension shaft
3. Remove scoop tool from regolith by pulling up in the opposite direction of insertion
4. Repeat motion three times

On a scale of 1 to 5, (1 meaning little to no rigidity and 5 meaning completely rigid), how stable did the mechanism feel during this operation?

Rigid = displacement/movement of the tool end relative to the extension handle shaft

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it to operate the tool?

**Torsion Control**

1. Place one hand on each shaft handle
2. Lightly plunge scoop tool into regolith
3. Rotate counterclockwise
   a. User will note scoop tool response and assess apparent rigidity
4. Repeat rotation in clockwise motion
   a. User will note scoop tool response and assess apparent rigidity

On a scale of 1 to 5, (1 meaning little to no rigidity and 5 meaning completely rigid), how stable did the mechanism feel during this operation?

Rigid = displacement/movement of the tool end relative to the handle shaft

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it to rotate the tool?

**Regolith Retrieval**

1. Place one hand on each shaft handle
2. Plunge scoop tool into regolith
3. Relocate non-dominant hand to the center of the shaft handle
4. Position dominant hand on the extension shaft
5. Scoop regolith by using a shoveling motion, bringing the scoop head to an upright position
   a. User will note assembly response, assessing apparent rigidity and amount of regolith retained
6. Discard regolith

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it to obtain a sample?

On a scale of 1 to 5, (1 meaning little to no rigidity and 5 meaning completely rigid), how stable did the mechanism feel during this operation?

On a scale of 1 to 5, (1 meaning ineffective and 5 meaning completely effective), how successful was this device as a scoop tool?

Drop Test

1. Disassemble the mechanism by rotating the cam handle 90 degrees and removing the tool-end insert from the receiver
2. Drop both parts, allowing for complete contact with NBL floor
3. Retrieve extension shaft with dominant hand
4. Ensure actuation handle is rotated to open position
5. Hold the shaft away from body in horizontal position
6. Rotate shaft to vertical position, with the receiving end pointed towards the floor
7. Repeat step 5 and 6
8. Retrieve scoop tool with non-dominant hand
9. Hold the tool end away from body in horizontal position
10. Rotate tool to vertical position, scoop facing upward
11. Repeat step 9 and 10
12. Orient the alignment mark on the tool-end with the actuation handle
13. With the actuation handle in the open position, insert the tool-end into the receiver

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it to insert the scoop into the mechanism?

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it closing the actuation handle?

14. Rotate the actuation handle to the closed position

On a scale of 1 to 5, (1 meaning very difficult and 5 meaning little to no difficulty), how easy was it closing the actuation handle?

15. Obtain regolith sample following regolith retrieval procedure

On a scale of 1 to 5, (1 meaning little to no rigidity and 5 meaning completely rigid), how stable did the mechanism feel during the regolith retrieval operation?

On a scale of 1 to 5, (1 meaning ineffective and 5 meaning completely effective), how successful was this device as a scoop tool?
Failure Recovery Plans

Mechanism Binds During Disengagement

1. Re-engage the actuation handle
2. Open the cam
3. Complete disengagement

Cam Alignment Fails

1. Disengage cam
2. Re-start engagement procedure

Cam Opens Unintentionally

1. Remove tool-end from the receiver
2. Return to step 1 of mechanism engagement procedure

Dust Clogs Mechanism

1. Disassemble mechanism
2. Complete dust removal procedure
3. Re-assemble mechanism