Design and Testing of the Microspine Gripper Tool for the Asteroid Redirect Mission

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Abstract: **The upcoming Asteroid Redirect Mission relies on the spacecraft's ability to grip, anchor, and maneuver a large boulder (1m-4m diameter) in microgravity. This is achieved by using two microspine gripper tools on robotic arms to capture the boulder and react the forces of drilling and anchoring into the rock. Two iterations of the tool have been created and rigorously tested by the engineers in the Extreme Environment Robotics Group (347C) and the 3.0 Tool is in the final stages of the design process.**

In order to maximize grip force, the gripper has a hierarchy of compliance to keep every microspine engaged with the rock surface. Twenty-four linkages keep carriages of microspines pressed to the surface, complying with 1cm- scale roughness and providing the required motion to engage the microspines. Within the carriages, flexures are used to engage single microspines to 1mm-scale surface asperities. Several designs for the linkages, flexures, and microspines have been proposed and iterated. After rigorous testing of each variable, we present the best configuration of the compliant system for use on the 3.0 Microspine Gripper Tool for the Asteroid Redirect Mission.

I. Introduction

The Asteroid Redirect Mission (ARM) aims to create an unmanned spacecraft that will be able to approach a near-Earth asteroid and alter its path to potentially avoid a collision with Earth. The redirect maneuver will be performed using a gravity tractor, a flight path that places the spacecraft in an offset orbit around the target asteroid resulting in a net gravitational force on the body that can alter its trajectory over time. This strategy works best with a spacecraft of higher mass, since larger mass correlates to larger gravitational force on the asteroid. However, launching a probe of the required mass would be both inefficient and costly, so the mass must be acquired from a body already free of Earth's gravity.

Asteroids often have large boulders scattered across their surfaces that remain captive due to the microgravity of the asteroid. A boulder on the surface of the asteroid of about 1m-4m in diameter would contain the necessary mass to create an effective gravity tractor. This means that the spacecraft must approach the asteroid, select a boulder of appropriate size, land on the surface, and capture the boulder before it can push off and begin applying the gravity tractor maneuver.

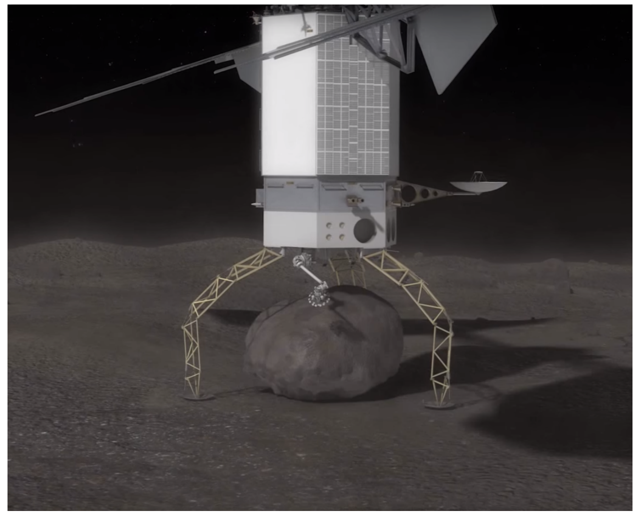

Figure 1: Artist's rendering of the ARM spacecraft capturing a boulder.

To capture the boulder, two microspine gripper drills will be used as end-effectors on seven degree of freedom (DOF) robot arms. These tools will be able to engage the surface, react the forces of drilling back into the rock surface, and set permanent anchors in order to rigidly couple the spacecraft and boulder at two points. Since the asteroid itself will be only a few kilometers in diameter, gravity will be much too small to react the weight-on-bit (WOB) forces required to break the surface of the boulder with the drill. In order to solve this problem the microspine grippers must engage the surface with strong enough grip so that the drill can bore a hole and set the anchor without leveraging off of the boulder surface. This paper details the design and testing of the gripper components on rock surfaces in comparison to the required WOB to drill.

II. PRIOR WORK

Prior to the testing detailed in this paper, two iterations of the microspine gripper tool had been built and tested. Since the 2.0 Tool, significant changes have been made to the way the microspines are actuated and engaged with the surface.

The 3.0 Tool is designed with a hierarchal structure for optimal compliances with surface irregularities so that as many microspines as possible can be engaged with the surface at a given time. The 7-DOF robotic arms on the spacecraft will comply to 10-cm scale irregularities, placing the grippers in optimal positions. Then, twenty-four linkages will lower to the surface, each conforming to 1-cm scale roughness. The linkages also are responsible for pulling the cassettes of 15-20 microspines towards the center of the gripper, providing the motion that enables a grip. Each microspine is individually compliant in the cassette since it is sprung in the x and z directions on a flexure. The flexures enable 1-mm scale compliance, allowing each microspine to find its own asperity to grip to. Two designs of each component were prepared for comparative testing: linkage designs 3.0 and 1.2, flexure designs EZ Blended and HS 12 Beam, and microspine designs Umpqua and Matsuo.

Additionally, a test stand was constructed, capable of replicating the motion of the 3.0 Tool and measuring the resulting grip forces created by a single hierarchal toe assembly. Several rock samples were selected to best mimic asteroid material, each subjected to testing on the test stand.

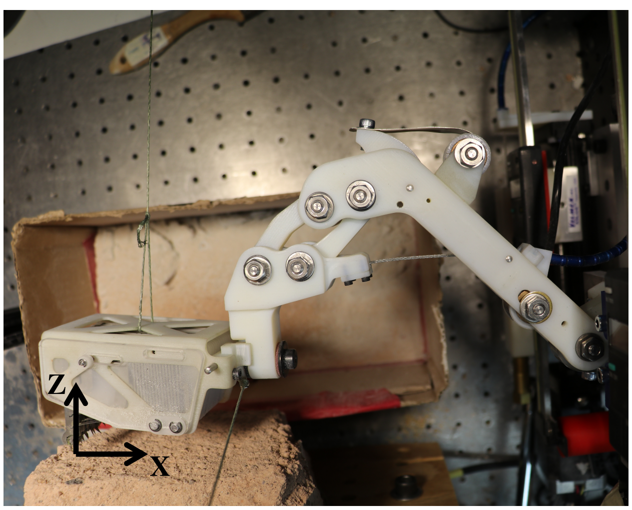

Figure 2: A single toe assembly consisting of a linkage (3.0), a cassette of flexures (EZ Blended), and microspines (Umpqua) on the test stand being tested on the surface of a rock sample (Rhyolite).

III. INITIAL DESIGN TESTING

The first round of testing involved a thorough analysis of the performance of each preexisting linkage and flexure design. Linkages 3.0, 1.2, and 1.3 were tested along with flexures EZ Blended and HS 12 Beam. Each design pair was tested on each rock sample.

The rock samples were made of either Rhyolite, a hard and friable rock likely to be similar to the hardest asteroid materials, or 700kPa Simulant, a soft, synthetic material with properties similar to those of comets. These rock samples represented the upper and lower limits of rock hardness expected. Previous grippers were tested on other rock samples such as Saddleback or Pumice, but both proved to be easy to grip in all cases, making results less useful than rock types that cause failure in some cases and success in others. Other potential rock types were omitted from these tests in the interest of saving time.

Tests were also conducted with different rock profiles. This variable changed the angle of the rock surface with respect to the motion of the gripper. Since the target boulder could be 1m-4m in diameter, the grippers will encounter surfaces of different curvatures depending on the boulder size. This curvature change can be extremely important, and each test set included three different rock profiles: flat, 10°, and 39°. These represent the worst-case scenario, a boulder of 4m, and a boulder of 1m, respectively.

In total, every combination of linkage, flexure, rock type, and rock profiles was tested. Data collected included grip force (z-force), shear force (x-force), and high-zoom video of the spines interfacing with the rock surface. The goal was to optimize the design to provide the highest grip force possible.

Results showed that linkage 3.0 outperformed 1.2 and 1.3 on all rock samples and profiles. We hypothesize that this is due to linkage 3.0 having a longer reach, giving it a more horizontal pull vector, or direction in which the force is applied to the microspines. A more horizontal pull vector allows the spines to catch on asperities in the rock surface, and more vertical motion pulls the spines off the surface, disengaging the spines and loosening the grip.

Additionally, flexure design EZ Blended produced the same or better grip force than HS 12

Beam in all tests. Our belief is that the decoupling of x and z compliances in the EZ Blended design helps to keep the spines engaged in asperities longer, increasing the grip force achieved. Results also showed that steeper angles (corresponding to smaller boulder diameters) corresponded to better grip forces due to a component of the shear force adding to grip force.

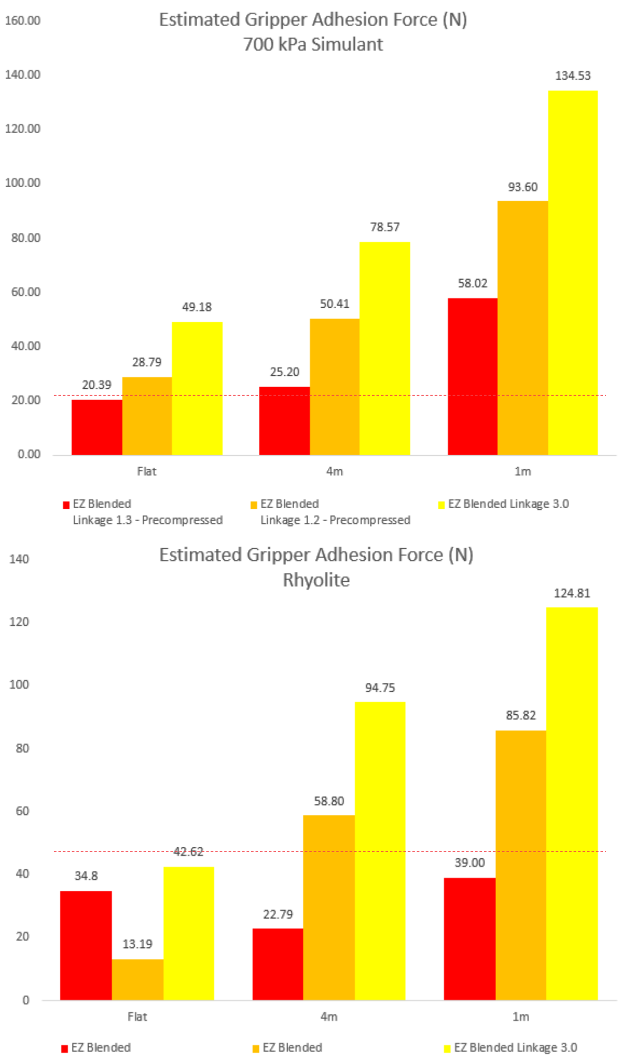

Figure 3: Test results of linkage testing, showing grip forces on 700kPa Simulant (top) and Rhyolite (bottom) with linkage 3.0 (yellow) outperforming linkage 1.3 (red) and linkage 1.2 (orange) in every case. The red lines correspond to the WOB requirement for each rock type. As shown, even the best performance on flat Rhyolite could not reach the WOB, and performance must be improved to be viable.

IV. Redesign and Retesting

With the results of the first round of testing analyzed, the team began redesigning the linkages and flexures to improve performance in the next round of testing. Several new flexure designs were considered, and ultimately the SL 3 Hook and SL 1 Hook designs were chosen for consideration. Additionally, the next round of testing would bring microspine designs into consideration. The previous round was solely using Umpqua hooks mounted at 60°, and this round would consider Matsuo hooks mounted at both 45° and 60°.

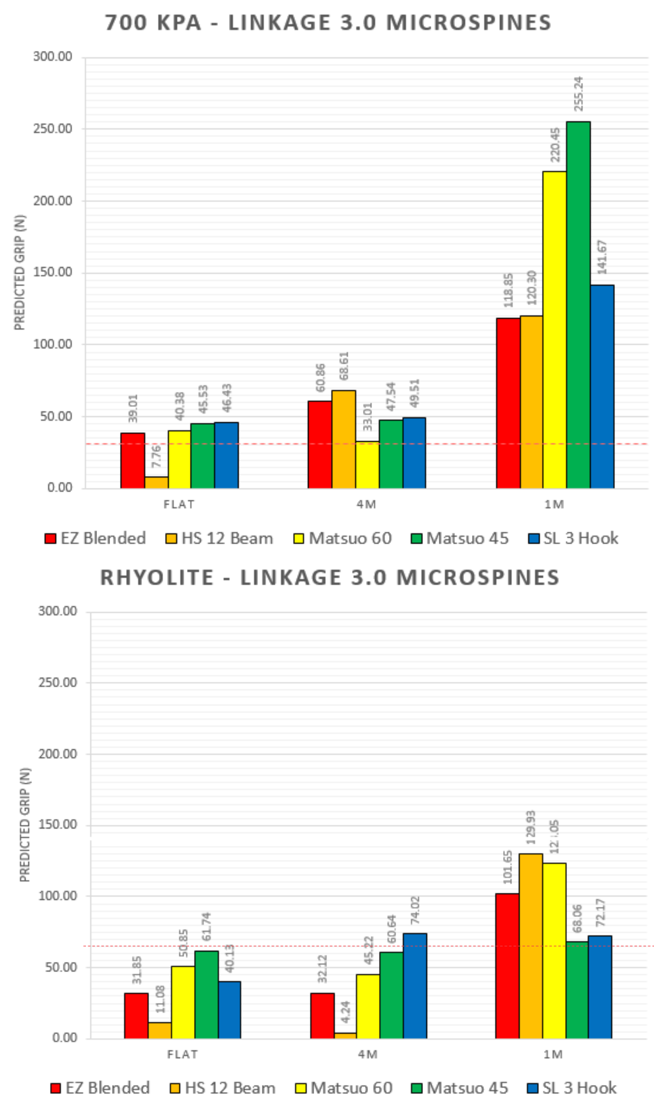

Figure 4: Test results of flexure testing, showing grip forces on 700kPa Simulant (top) and Rhyolite (bottom) with EZ Blended with Umpqua hooks (red), HS 12 Beam with Umpqua hooks (orange), EZ Blended with Matsuo hooks at 60º (green), and EZ Blended with Matsuo hooks at 45º (blue). The red lines correspond to the WOB requirement for each rock type.

The new flexure design SL 3 Hook was able to triple the number of microspines in contact with the surface by containing three independently compliant microspines on each flexure. Its performance was somewhat hindered by high friction between flexures and cassette deformation during use, but showed some promise when compared to EZ Blended. The new design performed comparably on flat and 10° samples, but noticeably worse on 39[9] samples.

To alleviate problems of friction and keeping all three spines on the surface simultaneously, the SL design was reduced to only one hook per flexure. This SL 1 Hook Design performed significantly worse than the SL 3 Hook design, confirming the suspicion that more microspines can better load share and create better grip forces.

Though changing microspine designs was not expected to affect grip force much, the Matsuo hooks outperformed the Umpqua hooks in many situations. Additionally, altering the hook mount angle caused a significant change in the grip force. This led to questions about how individual microspines behave under different conditions on the rock surface, and a new study was designed to solve this problem.

V. Single Flexure Testing

In order to more closely examine the effects of different microspine designs and angles, a third round of testing was initiated. This time a special cassette was designed to hold only one flexure at a time, and tests were run on more controlled surfaces to eliminate possible confounding variables. The present leading designs, linkage 3.0 and flexure EZ Blended were selected for the test. Additionally, rock samples were changed to include Sanded Pumice, Rhyolite, and Saddleback due to their consistent surface quality, and only flat samples were included.

In testing microspine performance three were chosen, Umpqua #6 hooks (the original standard), Matsuo hooks (the current leader), and Umpqua #2 hooks (a larger version of the #6 hooks). Both 60° and 45° mount angles were used in this test. Each was tested on all three surfaces, then when sufficiently dull tested again as a dull hook. This enabled direct comparison between the three types of hook, the two hook mount angles, and the hook sharpness. Unlike the previous testing, the x force was measured instead of grip force due to it being more consistent and less prone to noise from the load cell. Statistical evidence exists to show that x force and z force have a strong positive correlation, so this data can be used to make decisions regarding maximizing z force. After collecting and analyzing all data, the Umpqua #2 hook mounted at 60° was selected for use in future designs.

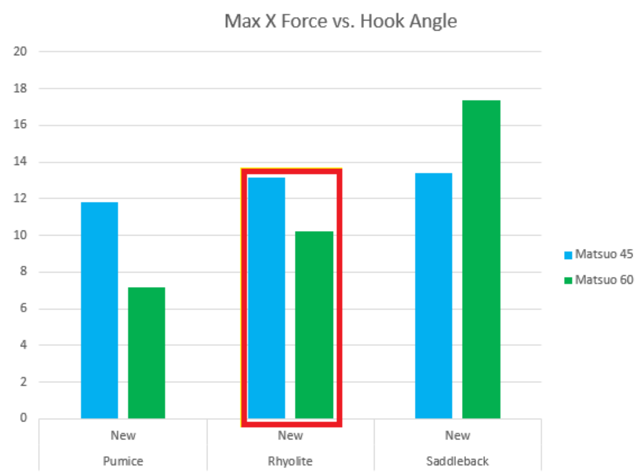

Figure 5: Test results* of hook angle testing of new Matsuo hooks on different rock surfaces.

A. *Spine Mount Angle*

Though the differences between distributions of data for spines at 45° and 60° are often not statistically significant, it seems that on softer rocks the 45° spines perform better than 60° spines. On harder rocks the opposite is true.

On soft rocks such as Pumice or friable rocks like Rhyolite the spine is able to break into the rock surface, forming its own asperity to catch on. The 45° spine is able to find this pocket better than the more upright 60° hook, which is more likely to pass over it. When the 60° hook breaks out of an asperity, it often jumps off of the rock surface momentarily and skips over the resulting pocket, whereas the 45° spine is more likely to make an asperity then move forward along the surface, finding the new asperity efficiently. On hard rocks such as Saddleback the hook cannot penetrate the surface, and 60° hooks are better at catching on the small, shallow, steep sided pits on the surface of Saddleback.

* The red boxes indicate that the enclosed data points are statistically indistinguishable by a Wilcoxon Rank Sum probability test with 90% confidence. These points should be regarded as the same.

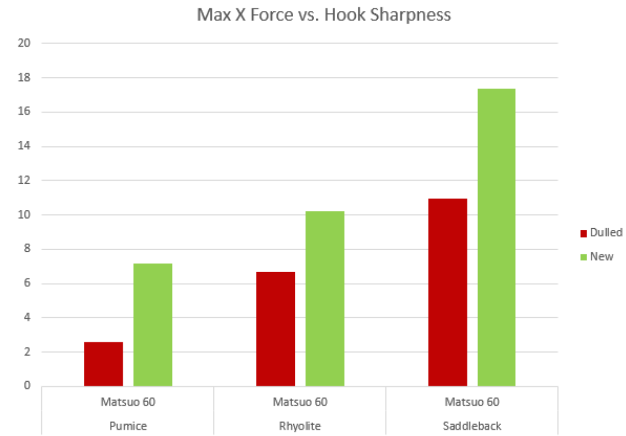

Figure 6: Test results[*] of hook angle testing of Matsuo 60º hooks on different rock surfaces.

B. Spine Sharpness

Sharp spines perform significantly better than dull spines, especially on soft rock such as Pumice. However, in harder rocks the difference is mostly negligible; dull and sharp spines perform the same on Saddleback.

On soft rocks such as Pumice, the spines are able to dig into the surface. This is better in sharp spines as they have the same force distributed over a smaller contact area, leading to a higher pressure and more likely digging deeper into the rock forming a strong grip. On friable rocks such as Rhyolite, the sharper spines are able to find and take advantage of tiny cracks in the surface whereas dull spines pass over the cracks, preferring more pronounced asperities that are more prone to breaking. On hard rocks such as Saddleback, the difference between the sharp and dull hooks is negligible in most cases since the asperities are large enough for all hooks and the hook is more likely to bend or break before the rock does. In terms of dulling the hooks, Pumice barely affects the hooks, Rhyolite noticeably dulls and occasionally bends the hooks, and Saddleback quickly dulls and bends the hooks.

C. Spine Type

The performance of the new spines on rock surfaces is mostly independent of spine type and size. The only test results that are statistically distinguishable from the others are the better performance of larger Umpqua spines on Pumice and Rhyolite and Matsuo spines on Saddleback.

The make of the hook does not affect the individual performance, though the temper of the steel may affect the amount of dulling over a series of trials. Matsuo hooks are make of softer steel, more prone to bending than Umpqua hooks, but this does not significantly affect single trial data. Noise or high variation may have caused the spike in Matsuo 60º result on Saddleback. The geometry of the hook does affect the performance, especially in soft rocks. As a hook cuts through Pumice it builds up compacted material in front of it, which helps to strengthen the grip on the surface. A larger hook builds up more of this material over its larger surface area, and can thus grip better on softer rocks than smaller hooks.

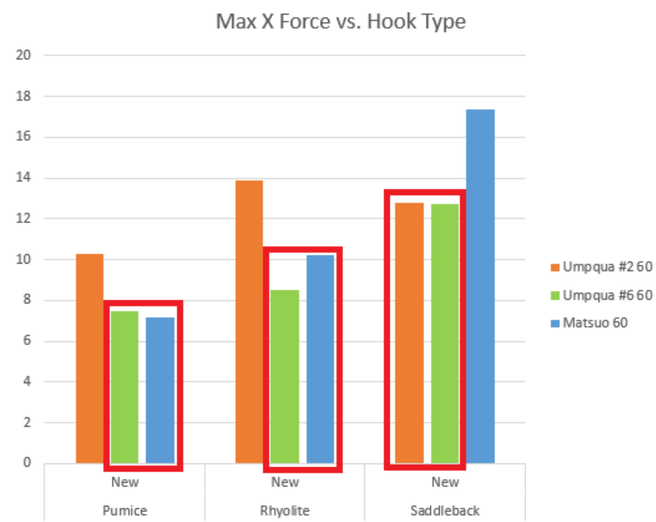

Figure 7: Test results[*] of hook type testing of new 60º hooks on different rock surfaces.

D. Tip Deformation

Though all the hooks start out with comparable tip radii, the thinner Umpqua #6 hooks tend to dull more than the thicker Umpqua #2 hooks when exposed to the same conditions. Though the Matsuo hooks seem to stay sharper than the Umpqua hooks, they have a tendency to bend very easily, changing the angle of the tip of the hook and robbing the used Matsuo hook of much of its gripping potential.

The Matsuo hooks are made of a different type of steel than the Umpqua hooks, and that makes

[*] In many other cases the difference between new and dull performance on Saddleback was statistically insignificant.

[*] The red boxes indicate that the enclosed data points are statistically indistinguishable by a Wilcoxon Rank Sum probability test with 90% confidence. These points should be regarded as the same.

them weaker to bending and deforming when experiencing high loads on the rock surface. The Umpqua hooks are less likely to bend but can fracture and dull more quickly than the Matsuo hooks. The dulling of the Umpqua hooks can be mitigated by using the #2 hook instead of the #6 hook since the #2 hook is thicker and thus requires more force to break the tip off.

Figure 8: Pictures of microspine tips before and after dulling, taken at 10X zoom.

VI. Future Work

At the conclusion of this testing, we have found the optimal configuration of linkage, flexure, and microspine designs within the set of current versions available. Future work will include altering and designing a new set of components, followed by a similar testing procedure.

During redesign of linkages, we have isolated six important linkage parameters; elevation spring k_e, return spring k_r, take-up spring k_t, travel length/location, take-up spring precompression, and pivot height. These parameters need to be individually optimized in the next linkage design. This process was started with linkage 3.1, a design that was created but not tested, but all parameters will be optimized for future design 4.0.

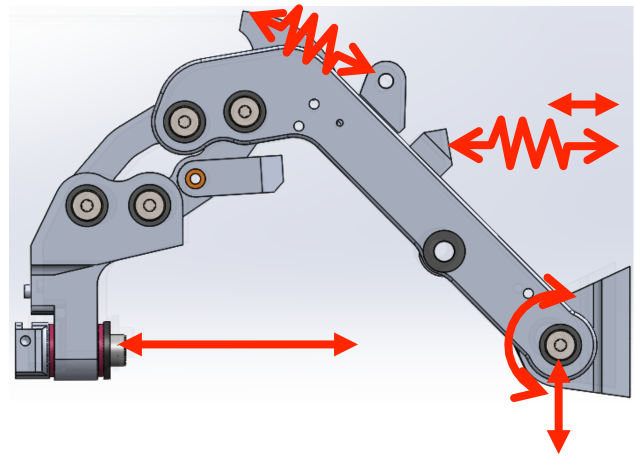

Figure 9: Linkage 3.0 with the six design parameters that will be optimized in the next design.

Also, rigorous testing has revealed minor design flaws in the EZ Blended flexure design, such as cassette jarring when releasing from an asperity, friction on the z-compliant track, and binding on alignment pints. An EZ Blended v2 design has been created to alleviate these problems and will require similar testing to verify an improvement.

Though a microspine type has been chosen as a result of the testing described, the hook mount angle will be tested at other angles such as 40°, 50^{0}, and 55° in order to determine a more optimal mount angle. Additionally, testing will need to be done to optimize the number of flexures per cassette, a value that could potentially have a large impact on grip force achieved.

In conclusion, the testing done in this study has moved the team several steps closer to an optimized design of the 3.0 Microspine Gripper Tool. By repeating this design-test-iterate strategy, the tool will soon be fully optimized and ready for deployment on the Asteroid Redirect Mission.

VII. Acknowledgements

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