# Design of an Excavation Robot: Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0

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**ABSTRACT**
*To continue on a sustainable and flexible path, NASA needs to address the challenge of collecting and moving large amounts of regolith at the destination*. Acquiring the water resources on Mars will require mining significant quantities of regolith and this is not possible with the state-of-the-art low mass excavation systems. Low gravity environments (Mars = 3/8 G) and launch mass restrictions limit the traction and the resulting reaction force of the vehicle, making current terrestrial techniques impractical. This project addressed this challenge by developing a completely new technology that can mine large quantities of regolith on Mars. Recent measurements by the "Curiosity" rover on Mars have found that the regolith contains ~ 2% water by weight globally, ~4% in Jezero Crater (Human Architecture Team's reference landing site), and much more at the poles (Leshin et al, 2013). *RASSOR 2.0 is a planetary excavator, which has a mass of 66 kg, with a 0.38 kg vehicle mass per kilogram, per hour of excavation rate and power usage of 4 W per kg of regolith excavation rate. A single RASSOR 2.0 can excavate a minimum of 2.7 metric tons of regolith per day.* This is accomplished by using counteracting excavation forces on two opposing digging implements called bucket drums and an autonomous mining control system. This work has addressed several major research areas outlined in the NASA Technology Area (TA) 04 Robotics & Autonomous Systems and TA 07 Human Destination Systems roadmaps. This project started at Technology Readiness Level (TRL) 4 as a low fidelity "proof of concept" prototype which has successfully demonstrated basic regolith simulant excavation functionality in a lab-scale gravity off load test. *The foundational technology described here was awarded US patent number: US 9027265 for a "Zero horizontal reaction force excavator" on May 12, 2015.*

## INTRODUCTION

NASA's strategic goal is to put humans on Mars in the 2030s. The NASA Human Spaceflight Architecture Team (HAT) has determined that In-Situ Resource Utilization (ISRU) is an essential technology to accomplish this mission. The HAT is considering transporting methane fuel from Earth to be used as propellant, with an oxidizer made from the carbon dioxide ($CO_2$) in the Martian atmosphere by using a Solid Oxide Electrolysis (SOE) reaction to extract oxygen (Craig et al, 2015). The, oxygen and methane will then be used for Mars Ascent Vehicle (MAV) return flight propellants. Given a finite payload capacity, and the high cost of space transportation, the primary drawback with this approach of bringing consumables, such as methane, from Earth is the reduction in the mission's capacity to bring additional supplies and equipment. An alternative approach is ISRU of the water found in the regolith on Mars which can be electrolyzed to produce oxygen and hydrogen for use in a Sabatier reaction with the $CO_2$ in the atmosphere, thus producing methane and water. The water can be used for life support, growing plants and/or radiation shielding. Electrolysis of the water also yields oxygen for propellants and breathing air. This method capitalizes on the resources found on Mars, reducing the reliance on Earth supplied consumables and promoting a sustainable Earth-independent architecture. By mining the regolith, future missions will not only extract the resources they need for life support and return propellant, but could also capture regolith for metals extraction, use the regolith as radiation shielding, produce raw material for three dimensional (3D) printing manufacturing/construction, and build infrastructure on Mars such as landing pads, berms, roads, un-pressurized structures and pressurized shelters. Mining regolith provides a cross-cutting capability that is highly beneficial to NASA space exploration. The RASSOR 2.0 project has developed new and novel technology that can mine large quantities of regolith on Mars and the Moon to that end, and a computer aided design (CAD) model is shown in Figure 1.

*Figure 1. Computer Aided Design (CAD) model of RASSOR 2.0 showing a mobility platform that carries two horizontal force cancelling and counter-rotating bucket drum excavation implements*

## RASSOR 2.0 CONCEPT OF OPERATIONS

RASSOR 2.0's conceptual mission is a human precursor or early cargo delivery to Mars to prove ISRU capabilities. A lander will carry the RASSOR 2.0 excavation system, a regolith feed system, and an ISRU processing plant. The acrobatic capabilities built into RASSOR 2.0 provides the system with enough torque to lower itself off the lander deck without the need for a separate motorized deployment system. Once on the surface, RASSOR 2.0 will drive to the designated mining site that is assumed to be 100 meters from the lander. On the first trip to the mining site RASSOR 2.0 will drive at a slow velocity while surveying the landscape using its stereo and hazard cameras. A virtual map of the hazards will be created and stored on board. For subsequent trips, RASSOR 2.0 will use a combination of the stored hazard map and low fidelity stereo vision to identify landmarks including its own wheel marks in the regolith to speed up travel time. Once at the mining site RASSOR 2.0 will lower its bucket drums and begin excavating regolith while slowly driving forward. RASSOR 2.0 also has the ability to excavate a slot trench to reach deeper regolith (>1.0 meter deep) that might have higher concentrations of water. The forward and aft arms have two bucket drum excavation implements that extend past the width of the wheel base which allows RASSOR 2.0 to excavate a trench and then drive into that trench to continue excavating. Automated excavation software will control the depth of cut and balance the excavation forces between the two sets of bucket drums. The opposing nature of the digging forces causes a net zero horizontal reaction force, so that vehicle traction is not necessary. RASSOR 2.0 will use torque sensing on the shoulder actuator to determine when the bucket drums are full and then return to the lander. Once at the lander, RASSOR 2.0 will position the bucket drums over a receiving hopper and deposit the regolith payload before beginning another regolith mining trip. Each 24 hour period will consist of 16 hours of mining operations and eight hours of recharging. Assuming a need of 10,000kg/ Earth-year of oxygen and a 1% yield from regolith processing, RASSOR 2.0 will excavate 1,000,000 kg of regolith per Earth-year. With RASSOR 2.0's payload capacity and an average velocity of 27 cm/s, this equates to 35 mining trips per day. RASSOR 2 has the capability of completing these trips much faster with a max velocity of 56.5 cm/s. These yield rates are conservative and consistent with a 4-person human class planetary mission architecture. If a higher amount of oxygen is needed, then more RASSOR 2.0 excavators can be deployed in a modular and scalable manner. However, with suspected higher water yields on Mars, then corresponding higher amounts of water can be mined, to be used for fueling the Mars Ascent Vehicle (MAV), life support, growing plants and other critical activities.

## DESIGN SOLUTION

### Bottom-Up Design Approach

In order to meet the mass and payload goals for the second generation of RASSOR the team completed the design with a bottom-up approach. The first generation of RASSOR (Mueller et al, 2013), provided insight into the overall system layout for RASSOR 2.0 such as the general location of the bucket drums, wheels, and arms. With the second generation, the team initially focused on the actuators and bucket drum subsystems. The actuators represent a very large fraction of the robot mass and the bucket drum payload goal was significantly increased from generation 1. Actuator prototypes were fabricated and evaluated on a custom test stand and gave insight into the actual performance metrics such as torque and efficiency. In a similar fashion, multiple prototype versions of the bucket drums were made and tested to evaluate capacity, payload loss, and regolith bridging. Significant effort was put into maturing and testing these designs before further system development was made. This method gave the design team confidence in the actual performance of the subsystems that was used to inform the next level of component identification and subsystem design. The actuator testing resulted in power draw numbers which helped to size total battery capacity. Also, the bucket drum testing informed the size needed for a bucket drum that would able to excavate and store the required amount of regolith. That sizing was then applied to the overall system CAD skeleton model and drove features such as the arm length and joint position. Subsystem integration into a full system CAD model did not occur until late in the design phase. Instead, the subsystems were fully developed, then floated in the CAD model where they were needed according to the evolving system skeleton. The "chassis" of RASSOR 2.0 then simply became the minimum structure needed to tie all the subsystems together. *This approach drastically reduced the overall mass (~50% reduction) with the added benefit of seeing regular progress on actual hardware as the subsystems were developed.*

**Wheels v. Tracks**

Based on many terrestrial excavators, tracks for mobility seems to be an obvious choice when considering a rugged mining design. RASSOR 1.5 utilized a track system for various technical, programmatic, and budget related reasons. The tracks on RASSOR 1.5 underwent many design iterations before a reliable design was achieved. Numerous complications associated with the use of tracks in Black Point 1 (BP-1) basalt planetary regolith simulant were encountered. RASSOR's unique ability to cancel horizontal excavation forces eliminated the need for a large draw pull allowing wheels to be considered for RASSOR 2.0. Free driving, draw bar and tilt table testing were performed to inform the wheels vs. tracks decision. For track testing a simplified version of RASSOR 1 was used with the RASSOR 2.0 mass simulated on it. A wheeled platform was developed where different diameters and wheel configurations could be tested in full Earth Gravity (1G). Table 1 shows the results from tilt table testing of Wheels vs. Tracks in a 1G environment.

**Table 1: Wheels vs Tracks 1G Tilt Table Test Results using BP-1 Regolith Simulant**

| Tilt Table Results | | | |
|---|---|---|---|
| | Angle | Successful Attempts | Total Attempts |
| Metallic Link Tracks | 25 | 1 | 3 |
| 13 inch with 4 Wheels | 25 | 1 | 3 |
| 13 inch with 6 Wheels | 25 | 1 | 3 |
| 17 inch with 4 Wheels | 25 | 3 | 3 |

Seventeen inch wheels performed comparably to tracks with subjective free driving tests. They also performed better in the tilt table testing, but had slightly less draw bar pull. Wheels inherently have less failure modes than tracks, so 17 inch wheels where selected for RASSOR 2.0. Analysis was also performed to predict wheel performance, but due to the non-co-operative and non-idealized BP-1 terrain, test results were found to be more informative regarding actual performance.

One interesting and useful phenomenon was the ability to vary the center of mass of the robot using, by moving the bucket drums' position, allowed different driving modes, increasing operational versatility.

**Contingencies**

RASSOR 2.0 is designed to be a rugged vehicle that routinely operates in environments that would immobilize most exploration rovers. For example the "Spirit" Mars Exploration Rover (MER) became immobilized when its wheels were stuck in soft regolith terrain. (Matson, 2010). As the regolith is excavated and churned up by the bucket drums, the ground can become very soft and uneven. In the event that RASSOR 2.0 becomes stuck in loose regolith, the bucket drums can be used as a contingency mobility system. RASSOR 2.0 can lower its arms to the point where the weight of the vehicle is distributed between the wheels and the bucket drums. This reduces the ground pressure to continue driving. Bucket drums loaded with regolith can also be used as counterweights to shift the center of gravity (CG) to enable climbing of steep slopes and recovery from various hazards. RASSOR 2.0 is also able to right itself if overturned by using its arms and bucket drums. On board sensors can detect if RASSOR 2.0 flips and an automated routine will right the vehicle. RASSOR 2.0 is also able to articulate into a position similar to a "Z" where the chassis is vertical and one set of bucket drums and wheels are on the ground while the second set of bucket drums reach out from the top of the chassis. This position gives RASSOR 2.0's stereo cameras a higher perspective that may be useful for surveying obstacles and a higher point of engagement for negotiation of a tall obstacle. The "Z" configuration also allows for dumping of regolith into a hopper without requiring a ramp for access.

**Custom Actuators**

In order to meet the low system mass requirements, three types of modular custom actuators were designed for RASSOR 2.0. All three types use the same conceptual design approach including a frameless motor, harmonic drive component set with a cross roller bearing and sensors for velocity and/or position, shown in Figure 2.

The shoulder joint actuator that is used to actuate the arm is the largest of the three. It utilizes a Parker K089050 frameless motor. The Parker K series kit motors allows for direct drive to the harmonic drive gear reduction decreasing the size and components that are inherently installed on traditional motors. This motor was then paired with the Harmonic Drive SHG 32-160 component set. With the 161:1 gear reduction, this size harmonic matches the output speed that is needed to perform the operations in the time required and has the torque capacity to lift and lower the arm with a bucket drum full of regolith. To react the loads imparted on this joint, a THK cross roller bearing was placed connecting the ground side and the rotating side to one another. This gives the advantage of reacting the radial, axial and moment loads within a single bearing. The need to know the absolute position of the arm was very important. Therefore a Netzer DS-70 absolute position sensor was mounted to the output side of the actuator. With a 19 bit angular resolution per 360 degrees it has an accuracy of less than 10 milli-degrees. For velocity control of the motor rotor, typical hall sensors did not have the resolution needed due to the slow velocity control needed for specific operations. Therefore a US Digital transmissive rotary disk and read head was used to close the velocity loop for velocity and position control. For the shoulder joint specifically, a brake was needed to hold that regolith payload while not powering the actuator. Additional, back driving the actuator when the power is off could cause damage and create problems for controls. To insure back driving is eliminated a custom electromagnetic safety brake was incorporated into the open cavity of the Harmonic Drive component set. Incorporating it into the open cavity of the harmonic set significantly reduced the overall length of the actuator. Rotary actuator characteristics are listed in Table 2.

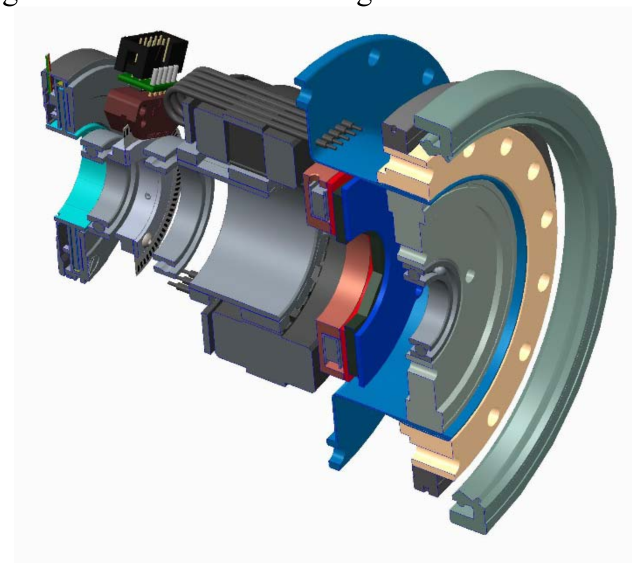

*Figure 2. Custom Rotary Actuator Section*

A CAD model was then constructed to design the housing that connects all the parts together. Due to all the components sharing the same axis, they were placed as tightly as possible keeping in mind the clearances per manufacturer's recommendations. Then the housing cross sections for all components were revolved and cutouts were made to lighten the structure. This methodology for design of the three actuator types greatly reduced the mass by eliminating redundant bearings, mounting flanges, and other components normally found if constructing each component individually then bolting them together. Due to the complexities of the shoulder joint and an opportunity to utilize a titanium 3D printer at NASA Marshall Space Flight Center (MSFC), it was decided to print the shoulder joint housing to save manufacturing time. Another design approach to save design and manufacturing time as well as reduce part count and complexity, was to use the same design for the bucket drum actuators and the drive actuators. Designing these custom actuators for the loads specific to RASSOR 2.0 enabled the mass of each individual actuator to be reduced over 50% below "off the shelf" systems with the same features.

**Table 2. RASSOR 2.0 Rotary Actuator Characteristics**

| | **Shoulder Actuator** | **Bucket Drum Actuator** | **Drive Actuator** |
|---|---|---|---|
| **Gear Ratio** | 161 | 161 | 161 |
| **Max Torque** | 644N*m (~5700in*lbf) | 191N*m (~1690in*lbf) | 191N*m (~1690in*lbf) |
| **Continuous Torque** | 236N*m (~2093in*lbf) | 93N*m (~821in*lbf) | 93N*m (~821in*lbf) |
| **Max Speed** | ~16 RPM | ~25 RPM | ~25 RPM |
| **Rated Speed** | ~10 RPM | ~18 RPM | ~18 RPM |
| **Velocity Feedback Resolution** | 10,000 counts/rev | 10,000 counts/rev | 10,000 counts/rev |
| **Position Feedback Resolution** | 19 bit (524288 counts/rev) | 19 bit (524288 counts/rev) | N/A |
| **Safety Brake** | yes | no | no |
| **Mass** | 3.58 kg (7.89 lbs) | 1.3 kg (2.87 lbs) | 1.17 kg (2.58 lbs) |

**Bucket Drum Design**

The RASSOR 2.0 Bucket Drum system is designed to hold a total of 80kg of regolith. Each drum consists of individual sections that include the digging scoops which are clocked to insure that one opposing scoop only is in contact with the excavating surface on each bucket drum. This is done to insure opposite reaction forces from forward to aft of the vehicle to assist excavating in low gravity. Testing shows that scoop number does not affect the volume of regolith each drum can hold while rotating, which maximizes at around 50% of the bucket drum volume. However, as the number of bucket scoops increase per section the amount of regolith lost during static drum operations goes up considerably. Conversely, not enough scoops requires additional thin cylinder segments to insure proper scoop contact. Each cylinder segment was designed with 2 scoops for a total of 8 individual buckets per drum. The digging scoop was designed with a serrated edge and rake angle to help reduce contact area to the surface in order to lower digging forces. The tooth rake angle creates a horizontal reaction force perpendicular to the gravity vector of the vehicle, therefore the bucket drum tooth angle is mirrored from one side of the vehicle to the other to equalize the forces. The rake angle of the scoops was designed where the scoops would act as self-anchoring once engaged into the regolith. This provides an increase in normal force during excavation allowing RASSOR 2.0 to drive and excavate at the same time. To minimize loss of regolith during operations each bucket incorporates a spiral baffle system to create an arduous path in order to retain the regolith. These baffles are critical to the function of the bucket drum because they must inhibit soil flow in one direction and allow the soil to flow freely when rotating the opposite direction. To minimize weight and maximize stiffness, the baffle system is fabricated out of 2 ply 12k carbon fiber. Machined 7075 Aluminum plates were used to separate the baffles and act as the structural backbone capable of supporting the weight of a fully loaded vehicle. Improved durability and wear is achieved by a hard coat anodizing of these plates. The entire assembly shown in Figure 3 was bonded together, minimizing fasteners to save weight.

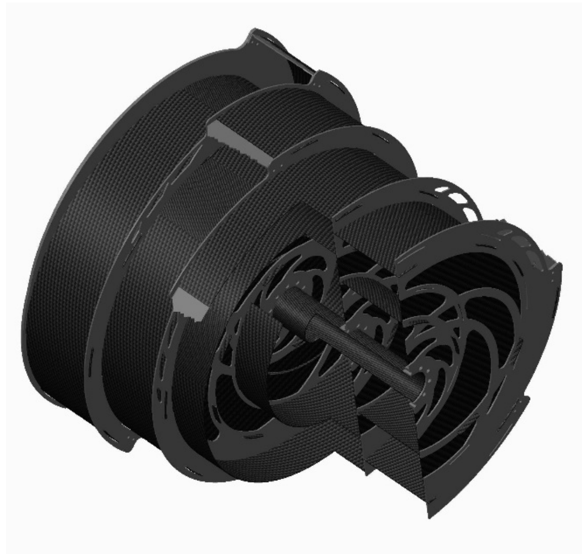

*Figure 3. Bucket Drum Assembly Section View*

**Automation and Sensing**

RASSOR 2.0 has an array of sensor feedback used for autonomy and control. The ten actuators in RASSOR 2.0 are equipped with incremental encoders and Hall Effect sensors for velocity and commutation feedback. The four bucket drums and two shoulder actuators are equipped with absolute encoders for position feedback. The incremental encoders are US Digital EM1 optical quadrature encoder modules with 10,000 counts per revolution. There are three Hall Effect sensors which are factory installed on the motor from Parker Bayside. The absolute encoders are single turn Netzer DS-70 with 19 bit resolution using SSI communication. The actuators are controlled by Elmo Motion Control G-Sol WHI20/100. The actuators' feedback sensors are directly read by the Elmo motor controllers and are used to close Proportional-Integral (PI) loops for position and velocity. The bucket drum and arm motor controllers use the absolute encoders and incremental encoders to perform a dual loop position over velocity closed loop control.

At a system level RASSOR 2.0 uses an Xsens MTI-30-2A5G4-O Inertial Measurement Unit (IMU), forward and aft stereo cameras, and forward and aft hazard cameras. All the cameras are Axis Communications model P1224-E. The main feedback for situational awareness are the stereo cameras. Using sensor fusion techniques the stereo cameras will be combined with the Inertial Measurement Unit (IMU) and feedback sensors on the actuators to close the loop for autonomy. RASSOR 2.0 is designed to be robust and purpose built for excavation without the need for sensitive instrumentation. Operations are fast and simple to achieve large masses of captured volatiles in the regolith. The autonomous software does not require precise sensors for feedback to provide situational awareness. The hazard cameras are used for inspection of the wheels and excavation. The hazard cameras can monitor or be used to quantify wheel sinkage, tank steer surcharge, and wheel slip. Also, dig depths and bridging as regolith enters scoops can be monitored on the bucket drums.

**Controls and Software Architecture**

RASSOR 2.0 is using open source Robot Operating System (ROS) as its software backbone. The software exists as two separate structures, one onboard RASSOR 2.0 and the other on the driver station. The onboard software is responsible for communicating with the motor controllers, sensors, and cameras. The onboard software is also responsible for publishing health and status to the driver station. The onboard software primarily has two modes of operations: tele-operation and autonomous. In the autonomous mode RASSOR 2.0 uses its array of sensors to perform the concept of operations autonomously while still providing health and status to the driver station. The autonomous mode has been simulated using ROS and Gazebo software. In tele-operation mode the onboard computer waits for commands from the driver stations to perform operations. The computer onboard RASSOR 2.0 is a RTD CMX32MVD1860HR-2048 F\S8GX. The driver station also has two modes of operation: supervisor and tele-operation. During supervisor mode the driver station accepts the health, status and pulls the Internet Protocol (IP) network camera stream from RASSOR 2.0. Supervisor mode is used while RASSOR 2.0 is running autonomously. During tele-operation the driver station has complete control of RASSOR 2.0 by streaming commands for the onboard computer to complete. Some semi-autonomous modes can be initiated during tele-operation, for example "Auto Dig". During "Auto Dig", the onboard computer will command the robot to drive straight at a given speed while balancing torque on both of the bucket drums. The computer being used as the driver station is a Microsoft Surface Pro 3 - 512GB / Intel Core i7. RASSOR 2.0 is using wireless communication to communicate between the onboard computer and the driver station. The radio being used is a Ubiquiti Networks PicoStation M2HP.

## LESSONS LEARNED AND GOOD PRACTICES

**Rework of the 3D printed titanium parts**

After the design was finalized for the shoulder actuators it was decided to utilize an opportunity to use a titanium 3d printer. This was decided due to many complex features that were added to the housing parts to be light weight which would increase conventional fabrication time. To get the models ready for 3D printing, material was added to the bearing surfaces, motor stator and rotor surfaces, and faces of the flanges where sealing surfaces were needed. Once the parts were 3D printed and shipped back to KSC, all of the added material needed to be machined down, creating a tight tolerance part where the motor, bearings, and harmonic drives were coaxial. This turned out to be very difficult to machine due to not having an axis of reference to start with. The machinist had to create many different fixtures to hold each of the six parts from both sides and assume an axis of revolution in each part. After all the fixtures were made and the parts completed it was found that 3D printing these parts took more time to complete due to the custom fixtures needed and the machinist could not guarantee coaxial alignment between each of the 6 components. In the end, the parts fit together perfectly and the actuator performed to the anticipated specification but at the cost of the extra time it took to ensure these components were correct. The lesson learned would be to add excess amounts of material to all critical surfaces so a machinist could get the parts as close to center as possible without worrying with the other critical dimensions due to the extra material added allowing for tolerance inconsistencies in the 3d printing process.

**Motor Selection**

During motor selection for the actuators, desired torque and speed requirements were identified. Motors were initially identified that would closely match the desired requirements, but after reviewing the motor curves at the 48 VDC bus, the motor's performance was reduced. Motors that were well match for speed and torque could not maintain continuous torque through the full range of rated speed. This is problematic because many of RASSOR 2.0's joints operate through a large range of speeds and torques. Initially this lead to selecting a motor one frame size larger to correct for the reduced torque near the max rated speed of the motor. The mass and size impact of selecting a larger motor was not desirable. After more research, two solutions were evaluated. First, increasing the bus voltage high enough to keep the continuous torque constant through the range of rated speed. Second, keep the 48 VDC bus and choose a motor winding which allows the continuous torque to be constant through the speed range but ultimately let the maximum rated speed be faster than initially anticipated. The first solution is the most appropriate, but required a custom battery to increase the bus above 100V or multiple batteries in series. Funding and time restraints did not allow for this solution. The second option could potentially affect performance at slower speeds, but after performing motor tests at different speeds and torques it was found that with proper tuning of the PI loops, performance was still acceptable at lower speeds.

**Wiring and Terminations**

Custom twisted pair cabling with external braided shielding was chosen for all wiring in RASSOR 2.0. Cable shielding terminations were a major source of problems for the project. Shielding was initially terminated by separating the braid near the connector and twisting the end so as to create a small length of wire. This wire was tinned and crimped with the appropriate contact and inserted into the connector housing along with the other wires. This termination approach created from the shielding was too large for the contacts and caused the contacts to short out to adjacent contacts in the housing. An initial fix to this problem was to trim out some strands of the braid out so that wire diameter was smaller and could fit into the contact properly. The result of this method was problematic as well, the trimmed stands of the braid tended to fan out and contact adjacent contacts in the housing, shorting the circuit. Two new approaches were used to successfully drain the braided shielding. In one approach, the end of the braided shield was folded back over itself, separated, and twisted into a short length of wire. This wire was then soldered to another wire that was the correct gauge for the contact. In the second approach, a length of bare cable was routed through the shielding along with the other conductors. This cable contacted the shielding throughout the cable and was terminated in a crimp and inserted into the housing.

Electrical connectors were also a major source of problems for the project. In general, many of the connectors were difficult to use resulting in bad connections because of their extremely small size and the unavailability of crimping tools. The selection of many of the connectors that were used was driven by the Elmo Solo Whistle motor controllers. The controller uses single and double row Tyco connectors, manual crimpers were available for the single row crimps, but not for the double row. Initially, generic crimpers were used to crimp the double row connectors. The connections appeared to be secure based on visual inspection and pull testing, however, after several connection/disconnection cycles the crimps would fail by either becoming loose on the wire or shearing the wire off. Somewhat better, but similar results occurred with the use of the correct crimps on the single row connectors. To fix the problem, Elmo factory cables with machine crimps were de-pinned from spare cables and reused in the necessary connectors.

**Stereo Camera Mounts**

Stereo cameras on each arm of RASSOR 2.0 are used to detect obstacles and aid in navigation. Typical machine vision stereo cameras have precisely positioned Charge Coupled Device (CCD) sensors so that the overlap between the images are aligned. The budget constraints on the current iteration of RASSOR 2.0 did not allow for procurement of the high fidelity machine vision stereo camera pairs. In order to test the concept of stereo vision on RASSOR 2.0, the team identified an IP camera solution from AXIS. The IP cameras have the desirable feature of separate modules for the CCD sensor and the actual encoder board. This allows for better packaging and enables two cameras to fit in the small space between RASSOR 2.0's bucket drums (as shown in Figure 4). The cameras can be configured to have multiple streams at different resolutions and frame rates which can be very useful for tele-operation that needs high frame rates, and image processing that benefits from high resolution. One issue with these cameras as a stereo pair is that the CCDs are not precisely positioned on the circuit board inside the camera housing. If two cameras are mounted inside the same tight tolerance rigid housing, they will produce images that are translated and rotated slightly from each other. The solution to this problem is a stereo camera housing that allows for adjustment and calibration of the stereo pair. The RASSOR 2.0 team designed a 3D-printed housing that incorporates adjustable and lockable ball and socket elements that the cameras are mounted to. The stereo pair was assembled into the housing and a test target was positioned in front of the cameras. Each camera was then adjusted until the overlap of the images was aligned and the mount was then secured. This enabled the team to create a very capable stereo vision pair at a fraction of the cost of a COTS system.

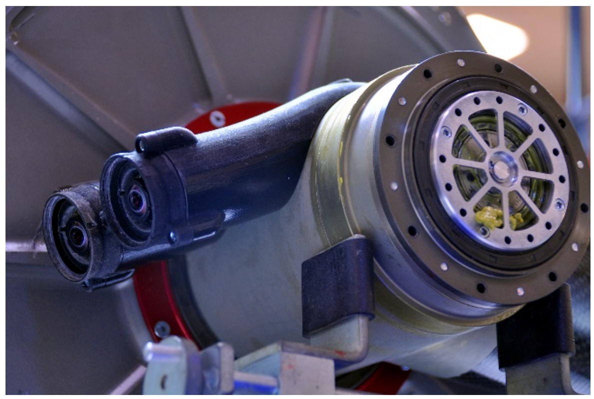

*Figure 4. Stereo Camera on Wrist Joint*

## SUMMARY

RASSOR 2.0 is a new iteration of a novel, compact and lightweight planetary excavator prototype which is capable of deep regolith excavation and slot trenching (> 1.0 m) in reduced gravity environments such as Mars (3/8 G) and the Moon (1/6 G). Precious and useful volatiles such as water ice are expected to be present at these depths in discrete polar locations. The RASSOR system mass was reduced by 50% which achieved the target of 66 kg total system mass, while also doubling the total regolith payload capacity to 80 kg. Tele-operations and autonomous modes were incorporated with stereo vision, and novel rotary actuators with extremely efficient packaging were developed and tested. RASSOR 2.0 has confirmed that this design is viable and could be considered (with further development) for future ISRU space missions, where regolith excavation and mining volatiles will be required.

The next iteration of this design: RASSOR 3.0, will raise the NASA Technology Readiness Level (TRL) from *TRL 4: Component/subsystem validation in laboratory environment* to *TRL 5: System/subsystem/component validation in relevant environment.* This will require thorough testing of prototypes in a representative environment. Basic technology elements must be integrated with reasonably realistic supporting elements. Prototyping implementations must conform to the target environment and interfaces. The biggest enhancement will be regarding thermal system control in a vacuum environment. Heat transfer and radiation into space will be required during the day and internal heat conservation will be required at night. A suitable battery that can survive extreme temperature events will also have to be sourced.

The successful approach of prototyping and testing will continue in order to advance this promising technology up the TRL ladder. When it achieves *TRL 6: System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space),* it will become a candidate for use in a future space mission.

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