NASA RMC: Lunabotics

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Motivation:
Why mine on the moon?
● Water is a precious resource for space missions
  ○ Human consumption, hygiene, plantation, radiation shielding, and rocket propellant
● Significant amounts of water are found in the icy regolith (gravel/rocks) underneath moon's surface
● Magnitudes more efficient than bringing resources from Earth

Why does NASA hold a collegiate competition?
● Challenge young engineers
● Produce new innovative ideas
The Competition:
- 50 collegiate teams compete
- The rubric and point system replicate the challenges of actually mining on the surface of the moon
- Each team has two attempts
  - 1kg of regolith required over both attempts to place
- Each attempt is 25 minutes
- Points are awarded for: regolith collected, dust tolerance, and degree of autonomy
- Points are deducted for: mass of robot, data bandwidth, and energy consumed

The Arena (below):
- 5.4m x 3.6m
- Collection zone, Obstacle zone, and Mining Zone
Design Problem Analysis

Constraints:

**Dimensional Constraints:**
1m x 0.5m x 0.5m

**Mass Constraints:**
60 kgs maximum

**Control Constraints:**
Full Autonomy during mining run

**Data Transfer Constraints:**
< 50 kb/s of data usage

Goals:

- At least 10 kg of regolith collected and deposited
- Completely closed-loop and sensor based code
- Preprogrammed failure modes
- Continuous auger-based mining system
- Structurally sound and efficient wheel and chassis design
2019 Design

- Size limits have been reduced to two thirds of previous competitions
  - Old length was near new limit, but not width nor height

- Test pit simulant behaved differently than competition simulant
  - Differences led to poor wheel performance
  - Plastic spokes failed in practice run

- Open loop controls led to wasted time

- Competition runs were not autonomous
Design Summary: Mining System

- On-robot storage and deposition arm/linkage
  - Stores up to 5kg of Regolith
  - Minimize drive time between Mining and Deposition locations

- Reduction of Auger Size
  - Auger driven by drive chain
  - Reduction in width of Auger Mount and Bearing

- Regolith transport system
  - Holes cut in auger casing with flexible tube to deposition Bucket
  - Gravity powered
Design Summary: Wheels and Chassis

- Cut down T-slots to size
  - Width cut down to 11.75 inches, length unchanged

- New motor configuration
  - Reoriented to save width
  - Utilizes bevel gears to transmit power
    - Gear teeth have max torque of ~445 inlb

- New wheel design
  - Minimizes width and height
  - Grousers added for traction
  - Final design will be single-piece metal casting
Design Summary: Wheels and Chassis

- Wheel axles modified to accommodate changes
  - Length minimized to fit on a single 2” T-slot
  - Motor-side shaft resized to 0.5” dia. to fit bevel gears
  - Limiting stress is torsion of the keyed 0.5” dia. aluminum
    - SF of 2 corresponds to a motor output power of 90W

- Total width required for wheels reduced from ~46cm to ~30cm
Design Summary: Control System

- Closed loop control
  - PID and other advanced control methods
  - Self tuning
  - Intelligent obstacle navigation
  - Failure detection and handling

- New hardware
  - Primary computer (LattePanda)
  - SLAMTEC S1 scanning LIDAR
  - Decawave TOF/RADAR ranging modules
  - Revamped power distribution system with current monitoring
  - Numerous accelerometers, gyroscopes, limit sensors, position sensors, etc.
Design Summary: Control System

- LattePanda Alpha 864s
  - Intel M3-7Y30 CPU (10nm)
    - As in the 2018 Macbook
    - Power efficient
    - Fast IO
  - Onboard wireless networking
  - Onboard Arduino compatible co-processor with GPIO
  - Standard software
    - Debian 10 Linux (amd64)
    - Python 3 (FOSS libraries)
    - Firmata (co-processor protocol)

- Expandability
  - Additional coprocessors
  - Neural net and machine learning accelerators
  - Compatible with ROS, Robotstudio, etc.
Final Concept

2020

2019
Final Concept
Final Concept

Designed for reliability and consistency:

- Modular chassis - Quick assembly/disassembly for repairs and modifications
- Onboard storage and sifting - consistent amount of regolith per mining run
- Closed loop, sensor based autonomy - Efficient obstacle handling, optimized actions
- Cast aluminum wheels - Strong, lightweight
- Improved auger - Competition proven, biggest limitation resolved
- Separate deposition arm with own motor
## Budget

<table>
<thead>
<tr>
<th>Expense</th>
<th>Cost</th>
<th>Expense</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round Trip Flight to Florida</td>
<td>$3,600</td>
<td>Control hardware</td>
<td>$500-1200</td>
</tr>
<tr>
<td>Hotel</td>
<td>$1300</td>
<td>Transportation at competition</td>
<td>$720</td>
</tr>
<tr>
<td>Prusa 3D Printer</td>
<td>$814.12</td>
<td>Food in Florida</td>
<td>$1350</td>
</tr>
<tr>
<td>New Simulant</td>
<td>$900</td>
<td>Other robot components</td>
<td>$1066</td>
</tr>
<tr>
<td>Shipping Robot to Florida</td>
<td>$208-$400</td>
<td>TOTAL</td>
<td>$10,000</td>
</tr>
</tbody>
</table>
## Validation/Testing Plan

<table>
<thead>
<tr>
<th>Objective</th>
<th>Metric</th>
<th>Target</th>
<th>Testing Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autonomous Operation</td>
<td># of inputs</td>
<td>0</td>
<td>Record number of controller inputs required by each test run.</td>
</tr>
<tr>
<td>Obstacle Detection</td>
<td># of obstacles contacted</td>
<td>0</td>
<td>Physical trials involving movement from starting zone to mining area.</td>
</tr>
<tr>
<td>Simulant Capacity</td>
<td>kg</td>
<td>&gt; 10 kg</td>
<td>Measure mass of mined simulant for each drilling run.</td>
</tr>
<tr>
<td>Mass</td>
<td>kg</td>
<td>≤ 60 kg</td>
<td>Weighing the robot on an industrial scale.</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>W-h</td>
<td>&lt;1000</td>
<td>Record power consumed by robot after each test run.</td>
</tr>
<tr>
<td>Dust Tolerance</td>
<td>%</td>
<td>&lt; 20%</td>
<td>Measure surface area of critical components contaminated with dust after each test run.</td>
</tr>
<tr>
<td>Data Transmission</td>
<td>kb/s</td>
<td>&lt;1</td>
<td>Record data transmission for each test run.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Metric</th>
<th>Limit</th>
<th>Testing Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>m</td>
<td>0.5 x 0.5 x 1.0</td>
<td>Measure physical dimensions of final robot.</td>
</tr>
<tr>
<td>Mass</td>
<td>kg</td>
<td>60</td>
<td>Weigh the final robot.</td>
</tr>
<tr>
<td>Mining Depth</td>
<td>m</td>
<td>&gt;0.30 &lt;0.45</td>
<td>Mark auger tube at max drilling depth for each test run and measure.</td>
</tr>
<tr>
<td>Deposition Height</td>
<td>m</td>
<td>&gt;0.5</td>
<td>Weigh the auger tube and elevate to max height, then measure clearance.</td>
</tr>
<tr>
<td>Kill Switch</td>
<td>Y/N</td>
<td>Y</td>
<td>Present or not present.</td>
</tr>
<tr>
<td>COTS Power Monitor</td>
<td>Y/N</td>
<td>Y</td>
<td>Present or not present.</td>
</tr>
<tr>
<td>Wireless Control</td>
<td>Y/N</td>
<td>Y</td>
<td>Present or not present.</td>
</tr>
<tr>
<td>Onboard Power</td>
<td>Y/N</td>
<td>Y</td>
<td>Present or not present.</td>
</tr>
<tr>
<td>Cost</td>
<td>$</td>
<td>$10,000</td>
<td>Compare expenditures to budget.</td>
</tr>
</tbody>
</table>
# Validation/Testing Plan

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>What is the process step, change or feature under investigation?</td>
<td>In what ways could the step, change or feature go wrong?</td>
<td>What is the impact on the customer if this failure is not prevented or corrected?</td>
<td>8</td>
<td>Stuck wheel, grit ingress into gearbox</td>
<td>4</td>
<td>Load sensing, routine maintenance</td>
<td>2</td>
<td>64</td>
<td>Clean and lubricate gearboxes, install dust protection</td>
</tr>
<tr>
<td>Robot accelerates</td>
<td>Aluminum gearbox teeth shear off</td>
<td>Motor seizure, immobilization</td>
<td>8</td>
<td>Stuck wheel, impact loading of axle</td>
<td>3</td>
<td>Load sensing, obstacle avoidance</td>
<td>4</td>
<td>96</td>
<td>Optimize design for collision/stacking and dynamic loading</td>
</tr>
<tr>
<td>Aluminum axle fails in shear</td>
<td>Severe axle damage, immobilization</td>
<td>8</td>
<td>Stuck wheel, impact loading of axle</td>
<td>3</td>
<td>Load sensing, obstacle avoidance</td>
<td>4</td>
<td>96</td>
<td>Optimize design for collision/stacking and dynamic loading</td>
<td>Brooks/Jacob</td>
</tr>
<tr>
<td>Robot mines regolith</td>
<td>Steel rod for augur pitching fails</td>
<td>Severe rod damage, inability to mine, immobilization</td>
<td>8</td>
<td>Deflection of augur due to rock impact</td>
<td>2</td>
<td>Visual Inspection</td>
<td>2</td>
<td>32</td>
<td>Create redundant support for major augur deflections</td>
</tr>
<tr>
<td>Rock becomes lodged in augur tube</td>
<td>Inability to mine, damage to augur and/or motor</td>
<td>7</td>
<td>Augur picks up unusually large stone</td>
<td>5</td>
<td>Load sensing, visual inspection</td>
<td>3</td>
<td>105</td>
<td>Optimize augur tube to accommodate stones of unusual size</td>
<td>Nathan</td>
</tr>
<tr>
<td>Robot uses LIDAR to map environment</td>
<td>LIDAR fails to detect crater or other obstacle</td>
<td>Bad pathology to objective, collision</td>
<td>7</td>
<td>LIDAR blindspot, poor environment reflectivity, dust</td>
<td>3</td>
<td>Visual Inspection, automatic pathing updates</td>
<td>3</td>
<td>63</td>
<td>Ensure minimal LIDAR blindspots, account for reflectivity</td>
</tr>
<tr>
<td>Robot uses DWM to locate collector bin</td>
<td>Robot fails to accurately locate itself</td>
<td>Lost mined regolith, collision, bad pathology to objective</td>
<td>7</td>
<td>DWM positional accuracy outside of tolerance</td>
<td>4</td>
<td>LIDAR as redundant positioning tool, visual inspection</td>
<td>2</td>
<td>56</td>
<td>Accommodate DWM inaccuracy, cross-check position</td>
</tr>
<tr>
<td>Robot uses motors</td>
<td>Battery depletes</td>
<td>Complete robot shutdown</td>
<td>8</td>
<td>Motor stall, improper charging, battery degradation</td>
<td>7</td>
<td>Charge sensor, load/current sensors</td>
<td>1</td>
<td>56</td>
<td>Ensure proper charging, optimize battery usage</td>
</tr>
<tr>
<td>Battery overheats</td>
<td>Fire, battery damage/explosion</td>
<td>10</td>
<td>Motor stall, load sensor failure, excessive power draw</td>
<td>3</td>
<td>Load/current sensors</td>
<td>2</td>
<td>60</td>
<td>Ensure working load sensors, optimize power draw</td>
<td>Jacob</td>
</tr>
</tbody>
</table>

Who is responsible for making sure the actions are completed?
Validation/Testing Plan

- Dust interference and EMI are greatest risks
- Mitigate dust creation and exposure
- Design and assemble with EMI in mind, use of flyback diodes, shorten wires
- Prevent overheating and short circuiting
- Sink heat from control box directly to frame
- Careful assembly procedure to prevent shorts

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Occurrence</th>
<th>Severity</th>
<th>Detection</th>
<th>Risk Priority Number (RPN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overheating</td>
<td>8</td>
<td>6</td>
<td>2</td>
<td>96</td>
</tr>
<tr>
<td>Electromagnetic Interference (EMI)</td>
<td>8</td>
<td>7</td>
<td>3</td>
<td>168</td>
</tr>
<tr>
<td>Short Circuit</td>
<td>4</td>
<td>10</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>Battery Depletion</td>
<td>8</td>
<td>8</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td>Dust Interference</td>
<td>10</td>
<td>7</td>
<td>3</td>
<td>210</td>
</tr>
</tbody>
</table>
Validation/Testing Plan

High risk test plan:

- Rock lodged in augur tube
  - Attempt to recreate the failure by mining/inserting large stones
  - Determine if the robot can dislodge the rocks on its own or if intervention is necessary

- Dust interference
  - Manually apply dust to LIDAR and other components and test performance
  - Determine tolerable limit of dust for said components
  - Do not test dust in motors but on the ingress protection used with the motors

- EM interference
  - Run motors and other components in proximity to sensors/antenna while monitoring
  - Determine severity of interference and develop tolerance or protection

Safety precautions:

- Azomite & Diatomaceous Earth Testing
  - Fitted Respirators
  - Full Bodysuits
  - Dust Protected Electronic Components

- High Torque Motor Testing
  - No loose hair/clothing
  - Easily Accessible Kill Switch
  - Current sensors to detect stall current

- Circuit Testing
  - Only one lead of Lipo Battery exposed at once
  - Covering for all wires to reduce risk of short circuit
Term 2 Work Plan

Projected Milestones/Deadlines:
Dec 31:   Completed manual controlled prototype
Jan 21:   Complete test pit construction
Feb 8:    Initial pit testing completed
Feb 22:   Base autonomy implemented
Mar 28:   Physical systems assembled
Apr 15:   Fully autonomous operation
May 1:    Final testing and small changes completed
May 1:    Documentation and recommendations for next team finalized
Questions?
Thank you!