Construction with Regolith

CLASS / SSERVI / FSI

The Technology and Future of In-Situ Resource Utilization (ISRU)

A Capstone Graduate Seminar

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Senior Technologist / Engineer

NASA

Kennedy Space Center – Swamp Works
Biography

- B.Sc. Mechanical Engineering, University of Miami
- M.S. Space Systems, Tech University of Delft, Netherlands
- M.B.A. Florida Institute of Technology
- ASCE Aerospace Division, Former National Chairman
- NASA Space Shuttle Engineer, ISS Engineer, Space Mission Architecture, Advanced Technology Development for Moon, Mars, Asteroids In-Situ Resource Utilization (ISRU), Robotics for Construction
- 28 Years Experience at NASA KSC, JSC and JPL
OH MAN. SWAMP WORKS.

AN ENTIRE BUILDING DEDICATED TO IN SITU RESOURCE UTILIZATION AND INVESTIGATION ON OTHER PLANETS AND ASTEROIDS! SCIENTISTS AND ENGINEERS FIGURING OUT HOW TO TEST THE LUNAR SURFACE FOR WATER AND MINE THE REGOLITH OF MARS FOR FUEL!

SWAMP WORKS

"WE'RE TRYING TO CLOSE THE LOOP ON LIFE SUPPORT," THEY SAID.

"TELL ME MORE?" I SAID.

AND THEY DID.

Expand human presence into the solar system and to the surface of Mars to advance exploration, science, innovation, benefits to humanity, and international collaboration.
Objectives

- Broad exposure to Planetary Surface Construction using regolith as a building material
- Regolith and indigenous materials
- Space Environments
- Infrastructure required for Surface Settlement
- Understand the robotic construction tasks required in various space environments
- Case Study 1: Robotic excavation of regolith
- Case Study 2: Paver Based VTVL Pad
- Case Study 2: 3D printing a habitat for humans
Pioneering in Space

Pioneering involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration.

Five Major Areas of Pioneering

- **ISRU: Resource Characterization and Mapping**
  Physical, mineral/chemical, and volatile/water

- **ISRU: Mission Consumable Production**
  Propellants, life support gases, fuel cell reactants, etc.

- **Civil Engineering & Surface Construction**
  Radiation shields, landing pads, roads, habitats, etc.

- **In-Situ Energy Generation, Storage & Transfer**
  Solar, electrical, thermal, chemical

- **In-Situ Manufacturing & Repair**
  Spare parts, wires, trusses, integrated structures, etc.

**ISRU is a capability involving multiple technical discipline elements** (mobility, regolith manipulation, regolith processing, reagent processing, product storage & delivery, power, manufacturing, etc.)

**Pioneering does not exist on its own.** By definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.
Lunar and Mars Resources

**Moon Resources**
- **Regolith:**
  - Ilmenite - 15%
  - FeO•TiO₂ (98.5%)
  - Pyroxene - 50%
  - CaO•SiO₂ (36.7%)
  - MgO•SiO₂ (29.2%)
  - FeO•SiO₂ (17.6%)
  - Al₂O₃•SiO₂ (9.6%)
  - TiO₂•SiO₂ (6.9%)
  - Olivine - 15%
  - 2MgO•SiO₂ (56.6%)
  - 2FeO•SiO₂ (42.7%)
  - Anorthite - 20%
  - CaO•Al₂O₃•SiO₂ (97.7%)
- **Water:** (? , >1000 ppm)
- **Solar Wind**
  - Hydrogen (50 - 100 ppm)
  - Carbon (100 - 150 ppm)
  - Nitrogen (50 - 100 ppm)
  - Helium (3 - 50 ppm)
  - ³He (4 - 20 ppb)

**Mars Resources**
- **Atmosphere**
  - Carbon Dioxide (95.5%)
  - Nitrogen (2.7%)
  - Argon (1.6%)
  - Oxygen (0.1%)
  - Water (210 ppm)
- **Regolith:**
  - Silicon Dioxide (43.5%)
  - Iron Oxide (18.2%)
  - Sulfur Trioxide (7.3%)
  - Aluminum Oxide (7.3%)
  - Magnesium Oxide (6.0%)
  - Calcium Oxide (5.8%)
  - Other (11.9%)
  - Water (2 to >50%)²

**Lunar Resources**
- Oxygen is the most abundant element on the Moon – 42% of the regolith
- Solar wind deposited volatile elements are available at low concentrations
- Metals and silicon are abundant
- Water may be available at poles
- Lunar mineral resources are understood at a global level with Apollo samples for calibration

**Mars Resources**
- Atmospheric gases, and in particular carbon dioxide (95.5 %) , are available everywhere at 6 to 10 torr (0.1 psi)
- Viking and Mars Odyssey data shows that water is wide spread but spatial *distribution and form of water/ice is not well understood* (hydrated clays and salts, permafrost, liquid aquifers, and/or dirty ice)
Asteroid Resources

Meteorite Types

- **Chondrites (ordinary, enstatite)**
  - Stones, chondrules, olivine, pyroxene, metal, sulfides, usually strong

- **Volatile-rich Carbonaceous Chondrites (CI, CM)**
  - Hydrated silicates, carbon compounds, refractory grains, very weak.

- **Other Carbonaceous (CO, CV, CK, CR, CH)**
  - Highly variable, chondrules, refractory grains, often as strong as ordinary chondrites

- **Achondrites**
  - Igneous rocks from partial melts or melt residues

- **Irons**
  - Almost all FeNi metal

- **Stony-Irons**
  - Mix of silicates and metal
Some Regolith Resources and their Uses

- Lunar oxygen: propellant, life support
- Iron, aluminum, titanium: structural elements
- Magnesium: less strong structural elements
- Regolith: sintered blocks, concrete, glass
- Water: Ice blocks, molded ice

Potential Applications
- Structural beams, rods, plates, cables
- Cast shapes for anchors, fasteners, bricks, flywheels, furniture
- Solar cells, wires for power generation and distribution
- Pipes and storage vessels for fuel, water, and other fluids
- Roads, foundations, shielding
- Spray coatings or linings for buildings
- Powdered metals for rocket fuels, insulation
- Fabrication in large quantities can be a difficult engineering problem in terms of materials handling and heat dissipation
Basalt, a mafic extrusive rock, is the most widespread of all igneous rocks, and comprises more than 90% of all volcanic rocks – it is commonly found on the Moon and Mars.

Source: www.geocaching.com
Terrestrial Concrete vs Basalt

Typical properties of normal strength Portland cement concrete are:

- **Density**: 2500 - 2900 kg/m$^3$ (140 - 150 lb/ft$^3$)
- Compressive strength: ~20 - 40 MPa (~3000 - 6000 psi)

Typical properties of Basalt rock are:

- **Density**: 2630 +/- 140 kg/m$^3$ (164 lb/ft$^3$)
- Compressive strength: ~144 - 292 MPa (20,885 – 42,351 psi)

Basalt rock can be 4-7 X stronger in compression than normal Portland cement concrete typically used on Earth.

How can basalt rock be formed to be comparable to concrete as a construction material?

*Sintered basalt regolith* has achieved **206 Mpa (30,000 psi) in compression tests** (ref: KSC Swamp Works with PISCES, Hawaii collaboration)

**5X stronger** than Portland Cement concrete – *turning regolith into rock!*
Lunar Regolith Definition

**Regolith**: Surficial layer covering the entire lunar surface ranging in thickness from meters to tens of meters formed by impact process – physical desegregation of larger fragments into smaller ones over time.
Basalt Granular Material
= Construction Material
Asteroid Regolith Fines

Soil Structure

- Relative to Lunar Soil NEAs have....
- Much higher thermal inertia, much lower gravity
- Expect courser soils, more boulders
- Micro-impacts and regolith gardening can result in size segregation. The solar wind may deplete the smallest size fraction and the larger materials are preferentially retained on the surface of the asteroid.
- Fine materials may be retained at depth in the soil profile.
Mars is full of Regolith Fines
The Moon

- Gravity ~1/6 of Earth G
- Hard vacuum (1x 10^{-12} torr)
- Large temperature swings (especially at Equator)
- Long night ( ~14 Earth-days)
- Very dusty
- Sharp, angular soil with high glass content
  - Very abrasive, electrostatically charged, 100 micron and less
- Soil very compacted below top 2-3 cm layer
  - But we don’t know about compaction in the polar craters
- Unprotected from space particle radiation
- Solar flux same as at Earth
- Heating comes almost entirely from the Sun (at night the lunar surface is warmed slightly by Earth).
Near Earth Asteroids

- Gravity negligible (1/1000th of Earth G)
- Hard vacuum
- May be “rubble piles”
- Might have regolith
- Regolith may be denuded of fine particles at the surface; may be gravelly with boulders
- Different types of asteroids
- Unprotected from particle radiation
- Solar flux same as at Earth
Mars

• Gravity ~3/8 of Earth G
• Atmospheric pressure ~1% of Earth’s, but varies seasonally by 30% as it freezes and unfreezes from the polar caps
• Wind only has 1% of force as Earth’s wind
• Mars has CO₂ frost & snow
• Sand carried by wind still abrades like on Earth
• Atmosphere mostly carbon dioxide
• Very dusty atmosphere; dust storms, dust devils
Mars, continued

• Radiation environment on the surface is bad
• Soil is weathered, behaves like terrestrial soil
• Soil is diverse
• Geology is complex
• Little is known about subsurface geology
• Mixture of CO2 and water ice and clathrates
  – Varying mechanical strength
  – Ice is on the surface at high latitudes
  – Ice is near the surface at moderate latitudes
  – Ice is deep beneath the surface at low latitudes
Multiple Sheltering Aspects Needed

- Exhaust Plume Protection
- Thermal Protection
- Radiation Protection
- Micro-meteoroid Protection
• Geotechnical engineering falls within Civil Engineering but very closely aligned with Geological sciences and engineering, as shown below:
Typical Systems Engineering Process

**Need/Opportunity Statement**

**Active/Passive Stakeholders**

**System Context Diagram**

**System Requirements**

**System Concept Definition**

**Stakeholders Requirements**

**Functional View**

**Physical View**

**System Architecture**

Recursive Iteration
Mars Site Planning: Functional Requirements

13.5 Surface Construction

Team 13: In-Situ Resource Utilization

Site Planning
- 13.5.1
  - Site Survey & Characterization
    - 13.5.1.1
  - Architectural Layout & Master Planning
    - 13.5.1.2
  - Civil Engineering Design
    - 13.5.1.3
  - Geospatial Information System (GIS) Configuration Control
    - 13.5.1.4 Tool

Surface & Subsurface Preparation
- 13.5.2
  - Road Construction
    - 13.5.2.1
  - Foundation Construction
    - 13.5.2.2
  - Utilidor Construction
    - 13.5.2.3
  - Terrain Shaping, Grading & Rock Clearing
    - 13.5.2.4

Structure & Habitat Fabrication
- 13.5.3
  - Construction Techniques & Methods
    - 13.5.3.1
  - In Situ Building Materials
    - 13.5.3.2
  - Access & Handling Equipment
    - 13.5.3.3
  - In Situ Robotic / Human Construction Equipment
    - 13.5.3.4

Radiation & Micro Meteoroid Debris Shielding
- 13.5.4
  - Radiation Shelters
    - 13.5.4.1
  - Shields for Nuclear Reactors
    - 13.5.4.2
  - Micrometeoroid Shielding
    - 13.5.4.3

Structure & Site Maintenance
- 13.5.5
  - Integrity & Preventative Maintenance
    - 13.5.5.1
  - Waste Management
    - 13.5.5.2
  - Facility Management
    - 13.5.5.3

Landing & Launch Site
- 13.5.6
  - Landing/Launch Pads
    - 13.5.6.1
  - Flume Debris Shielding
    - 13.5.6.2
  - Exhaust Flame Management
    - 13.5.6.4
  - Sheltered Propellant and Consumables Farms
    - 13.5.6.5
  - Mars Lightning Protection
    - 13.5.6.6

(ref. NASA 2005 ISRU Road Map)
Lunar Mission Space Civil Engineering Capability Concepts

- Excavation & Regolith Processing for H₂ & O₂ Production, Binders & Aggregates
- Propellant Processing with Lander & Pad Infrastructure
- Resource Prospecting – Looking for Resources
- Thermal Energy Storage Construction
- Construction of Consumables Depots for Crew & Power (O₂, H₂)

Habitat, Hangars, Dust Free Zones, Landing Pads, Berm, and Road Construction
<table>
<thead>
<tr>
<th>Planetary Surface Construction Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch/Landing Pads</td>
</tr>
<tr>
<td>Beacon/Navigation Aids</td>
</tr>
<tr>
<td>Lighting Systems</td>
</tr>
<tr>
<td>Communications Antenna Towers</td>
</tr>
<tr>
<td>Blast Protection Berms</td>
</tr>
<tr>
<td>Perimeter Pad Access &amp; Utility Roads</td>
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<tr>
<td>Spacecraft Refueling Infrastructure</td>
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<tr>
<td>Power Systems</td>
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<tr>
<td>Radiation, Thermal &amp; Micro Meteorite Shielding</td>
</tr>
<tr>
<td>Ablative Regolith Atmospheric Entry Heat Shields</td>
</tr>
<tr>
<td>Radiation Shielding for Fission Power Plants</td>
</tr>
<tr>
<td>Electrical Cable/ Utilities Trenches</td>
</tr>
<tr>
<td>Foundations / Leveling</td>
</tr>
<tr>
<td>Trenches for Habitat &amp; Element Burial</td>
</tr>
<tr>
<td>Regolith Shielding on Roof over Trenches</td>
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<tr>
<td>Equipment Shelters</td>
</tr>
<tr>
<td>Maintenance Hangars</td>
</tr>
<tr>
<td>Dust free zones</td>
</tr>
<tr>
<td>Thermal Wadi’s for night time</td>
</tr>
<tr>
<td>Radiation shielding panels for spacecraft</td>
</tr>
<tr>
<td>Regolith Mining for O$_2$ Production</td>
</tr>
<tr>
<td>H$_2$O Ice/Regolith Mining from Shadowed Craters</td>
</tr>
</tbody>
</table>
Specific Examples: Types of Structures

Habitats
• Landed self-contained structures
• Rigid modules (prefabricated/in situ)
• Inflatable modules/membranes (prefabricated/in situ)
• Tunneling/coring/trenches/underground
• Exploited caverns/lava tubes

Storage Facilities/Shelters
• Open tensile (tents/awning)
• Interlocking Elements with standard interfaces
• Modules (rigid/inflatable)
• Trenches/underground
• Ceramic/masonry (arches/tubes)
• Mobile
• Shells

Supporting Infrastructure
• Slabs/ foundations (melts/compaction/additives)
• Trusses/frames
• Berms for rocket blast protection
Top Space Regolith Construction Technical Challenges*

- Strength of In-situ derived regolith concrete materials
- New construction methods & equipment
- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Energy re-charging and work flow scheduling
- Encountering sub surface rock obstacles
- Long life cycle (5-10 years) and high reliability required
- Spare parts logistics, manufacturing and repair
- Unknown water ice / regolith composition and deep digging
- Extended lunar night time operation and power storage
- Thermal management
- Robust communications

*(no specific order)
Lunar Master Site Planning Considerations: Example

Mueller & King, 2007
Lunar Base Construction

Build Regolith Based Landing Pads and Berms for safe Vertical Take Off & Vertical Landing (VTVL) Operations

NASA Artwork by Maxwell
Lunar Surface Construction Tasks

Criteria for Lunar Outpost Excavation
R. P. Mueller and R. H. King
Space Resources Roundtable –SRR IX
October 26, 2007
Golden, Colorado

<table>
<thead>
<tr>
<th>Task</th>
<th>%</th>
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<tbody>
<tr>
<td>Trenching</td>
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<tr>
<td>Clearing and Compacting</td>
<td>42</td>
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<tr>
<td>Building Berms</td>
<td>18</td>
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<tr>
<td>Habitat Shielding</td>
<td>31</td>
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<tr>
<td>Ice Mining</td>
<td>17</td>
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<tr>
<td>Regolith Mining</td>
<td>83</td>
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<tr>
<td>Construction</td>
<td>84</td>
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<tr>
<td>Mining</td>
<td>16</td>
</tr>
</tbody>
</table>

Excavation Requirements by Task

- Cable Trenches
- Roads/Obstacle Removal
- Landing Pad
- Berms/Mitigation
- Foundations/Leveling
- Habitat Trench
- Habitat Shielding Roof
<table>
<thead>
<tr>
<th>TA4.1 Sensing &amp; Perception</th>
<th>TA4.2 Mobility</th>
<th>TA4.3 Manipulation</th>
<th>TA4.4 Human-Systems Int.</th>
<th>TA4.5 Autonomy</th>
<th>TA4.6 Autonomous Rendezvous &amp; Docking</th>
<th>TA4.7 RTA Systems Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA4.1.1 3-D Perception</td>
<td>TA4.2.1 Extreme Terrain Mobility</td>
<td>TA4.3.1 Robot Arms</td>
<td>TA4.4.1 Multi-Modal Human-Systems Interaction</td>
<td>TA4.5.1 Vehicle System Management &amp; FDIR</td>
<td>TA4.6.1 Relative Navigation Sensors (long-, mid-, near-range)</td>
<td></td>
</tr>
<tr>
<td>TA4.1.2 Relative Position &amp; Velocity Estimation</td>
<td>TA4.2.2 Below-Surface Mobility</td>
<td>TA4.3.2 Dexterous Manipulators</td>
<td>TA4.4.2 Supervisory Control</td>
<td>TA4.5.2 Dynamic Planning &amp; Sequencing Tools</td>
<td>TA4.6.2 Guidance Algorithms</td>
<td></td>
</tr>
<tr>
<td>TA4.1.3 Terrain Mapping, Classification &amp; Characterization</td>
<td>TA4.2.3 Above-Surface Mobility</td>
<td>TA4.3.3 Modeling of Contact Dynamics</td>
<td>TA4.4.3 Robot-to-Suit Interfaces</td>
<td>TA4.5.3 Autonomous Guidance &amp; Control</td>
<td>TA4.6.3 Docking &amp; Capture Mechanisms/Interfaces</td>
<td></td>
</tr>
<tr>
<td>TA4.1.4 Natural &amp; Man-made Object Recognition</td>
<td>TA4.2.4 Small Body / Microgravity Mobility</td>
<td>TA4.3.4 Mobile Manipulation</td>
<td>TA4.4.4 Intent Recognition &amp; Reaction</td>
<td>TA4.5.4 Multi-Agent Coordination</td>
<td>TA4.6.4 Mission/System Managers for Autonomy/Automation</td>
<td></td>
</tr>
<tr>
<td>TA4.1.5 Sensor Fusion for Sampling &amp; Manipulation</td>
<td>TA4.3.5 Collaborative Manipulation</td>
<td>TA4.4.5 Distributed Collaboration</td>
<td>TA4.5.5 Adjustable Autonomy</td>
<td>TA4.6.5 Terrain Relative Navigation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TA4.1.6 Onboard Science Data Analysis</td>
<td>TA4.3.6 Robotic Drilling &amp; Sample Processing</td>
<td>TA4.4.6 Common Human-Systems Interfaces</td>
<td>TA4.5.6 Path &amp; Motion Planning with Uncertainty</td>
<td>TA4.6.6 Onboard Computing</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>TA4.4.7 Safety, Trust, &amp; Interfacing of Robotic/Human Proximity Operations</td>
<td></td>
<td>NASA Roadmap 2012</td>
<td></td>
</tr>
</tbody>
</table>

NASA Roadmap 2012
Top Robotic Technical Challenges

• Object Recognition and Pose Estimation
• Fusing vision, tactile and force control for manipulation
• Achieving human-like performance for piloting vehicles
• Access to extreme terrain in zero, micro and reduced gravity
• Grappling and anchoring to asteroids and non cooperating objects
• Exceeding human-like dexterous manipulation
• Full immersion, telepresence with haptic and multi modal sensor feedback
• Understanding and expressing intent between humans and robots
• Verification of Autonomous Systems
• Supervised autonomy of force/contact tasks across time delay
• Rendezvous, proximity operations and docking in extreme conditions
• Mobile manipulation that is safe for working with and near humans

FIGURE 3. Additional Concepts From Top Left to Bottom Right: Auger, Bucket Ladder, Bucket Wheel or Bucket Drum, Dragline, Overshot Loader, and Scraper.


<table>
<thead>
<tr>
<th></th>
<th>Auger</th>
<th>Bucket Ladder</th>
<th>Bucket Wheel</th>
<th>Dragline</th>
<th>Overshot Loader</th>
<th>Scraper</th>
<th>Pneumatic</th>
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<tr>
<td>Production Cycle</td>
<td>134 min</td>
<td>134 min</td>
<td>134 min</td>
<td>224 min</td>
<td>176 min</td>
<td>176 min</td>
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<tr>
<td>Unloaded System Mass</td>
<td>17.8 kg</td>
<td>18.8 kg</td>
<td>19.8 kg</td>
<td>28.8 kg</td>
<td>16.8 kg</td>
<td>14.8 kg</td>
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<tr>
<td>Horizontal Reaction Force</td>
<td>11.5 N</td>
<td>12.2 N</td>
<td>12.8 N</td>
<td>18.1 N</td>
<td>10.9 N</td>
<td>5.6 N</td>
<td>Unknown</td>
</tr>
<tr>
<td>Vertical Reaction Force</td>
<td>14.4 N</td>
<td>15.3 N</td>
<td>16 N</td>
<td>0.4 N</td>
<td>13.6 N</td>
<td>12 N</td>
<td>Unknown</td>
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<tr>
<td>Subsystems</td>
<td>5</td>
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<td>6</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>6</td>
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<tr>
<td>Motor/gear assemblies</td>
<td>14</td>
<td>14</td>
<td>15</td>
<td>24</td>
<td>14</td>
<td>13</td>
<td>5</td>
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<tr>
<td>Material Transfer Points</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>3</td>
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</tbody>
</table>
60 Kg Excavator with Small Scoop

Replica of NASA Lunar Surveyor Scoop & Test results in regolith simulants
Design Options:

• Increase Traction (Heavier, grousers on wheels)
• Decrease Excavation Forces (Smaller scoops, less depth of cut)

• If a traditional small / lightweight excavator is designed, then the design solution must excavate many small scoops quickly to meet traction constraints and still meet production goals
What is the Best Lunabot Regolith Mining Design for the Moon??
The Most Popular Winning Design? (50-80 Kg)

2009: Paul’s Robotics WPI

2010: Montana State U

2011: Laurentian University

2012: Iowa State U
Or are these designs better?

2012: Embry Riddle Daytona AU

2011: U North Dakota

2012: FAMU/ Florida State U

2012: Montana State U
Regolith Excavation Mechanisms
All excavators from three Centennial Excavation Challenge Competitions (2007, 2008 and 2009) and two Lunabotics Mining Competitions (2010 and 2011)

<table>
<thead>
<tr>
<th>Regolith Excavation Mechanism</th>
<th># of machines employing excavation mechanism</th>
</tr>
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<tbody>
<tr>
<td>Bucket ladder (two chains)</td>
<td>29</td>
</tr>
<tr>
<td>Bucket belt</td>
<td>10</td>
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<tr>
<td>Bulldozer</td>
<td>10</td>
</tr>
<tr>
<td>Scraper</td>
<td>8</td>
</tr>
<tr>
<td>Auger plus conveyor belt / impeller</td>
<td>4</td>
</tr>
<tr>
<td>Backhoe</td>
<td>4</td>
</tr>
<tr>
<td>Bucket ladder (one chain)</td>
<td>4</td>
</tr>
<tr>
<td>Bucket wheel</td>
<td>4</td>
</tr>
<tr>
<td>Bucket drum</td>
<td>3</td>
</tr>
<tr>
<td>Claw / gripper scoop</td>
<td>2</td>
</tr>
<tr>
<td>Drums with metal plates (street sweeper)</td>
<td>2</td>
</tr>
<tr>
<td>Bucket ladder (four chains)</td>
<td>1</td>
</tr>
<tr>
<td>Magnetic wheels with scraper</td>
<td>1</td>
</tr>
<tr>
<td>Rotating tube entrance</td>
<td>1</td>
</tr>
<tr>
<td>Vertical auger</td>
<td>1</td>
</tr>
</tbody>
</table>
NASA KSC Swamp Works
Regolith Advanced Surface Systems Operations
Robot (RASSOR)

RASSOR 2.0 Prototype
Dry Mass ~ 66 Kg
Regolith Payload = 80 Kg
Counter-Rotating Bucket Drums = Zero Net Reaction Force

RASSOR 1.0 Prototype

RASSOR 1.5 Prototype
Excavator: RASSOR 2.0
Excavator: RASSOR 2.0

Video
Bucket drum torque test setup

<table>
<thead>
<tr>
<th>Cutting Depth (cm)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Avg.</th>
<th>Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.66</td>
<td>47.45</td>
<td>33.89</td>
<td>40.67</td>
<td>33.89</td>
<td>38.98</td>
<td>220.09</td>
</tr>
<tr>
<td>1.77</td>
<td>20.34</td>
<td>20.34</td>
<td>20.34</td>
<td>13.56</td>
<td>18.64</td>
<td>105.26</td>
</tr>
</tbody>
</table>

~275 N Digging Force @ 4 cm depth
Launch / Landing Pad Construction

Construct a Launch/Landing Pad using In Situ Regolith for rocket plume impingement mitigation.

Photo Credits: PISCES / NASA ACME

NASA/ PISCES Paver Laying Robot

Hawaii PISCES Rover on Mauna Kea with Payloads
ISRU Process Waste

Use of waste stream from In-Situ Resource Utilization (ISRU) processes.

- Hot regolith can be poured into a heat shield mold.
- Saves energy by combining processes.

Hot Hawaiian tephra output from the ROxygen generation I oxygen production reactor.

This basalt regolith material can be used to make parts and pavers for lunar structures.
Temperature and heating time are crucial factors in resulting structure.

Sintered Basalt Regolith results in a high temperature resistant material that can be used for launch/landing pad materials.

JSC-1A sintered tiles that have been exposed to a rocket plume for a lander vehicle (Courtesy Swamp Works, NASA KSC)
Sintered Basalt Pavers

- Rock crusher fines (≤150µm)
- Sintered Basalt fines
- Utilized floating mold design to relieve cooling stresses
PISCES Rover, Helelani: Multi Purpose Vehicle.
Mobile Platform Base: Alpha Argo Rover

Grading & Leveling Blade

Compactor Roller

Paver Deployment Mechanism

1,270 mm x 406 mm Steel Blade

1200 mm x 450mm (diam) Roller (1.9m³)

SWAMP WORKS
NASA KENNEDY SPACE CENTER

PISCES
PACIFIC INTERNATIONAL SPACE CENTER FOR EXPLORATION SYSTEMS | PISCES.HAWAII.GOV

Argo

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation
Launch / Landing Pad Construction

Photo Credits: PISCES / NASA ACME
Hawaiian Hot Fire Test!

~1,000 lbf Thrust, “M” Class Solid Rocket Motor Firing in test stand
Paver cracking led to new, improved sintered basalt material being developed
Robotic 3D Additive Construction using Regolith Concrete

2005 Concept: NASA / Marshall Space Flight Center
3D Additive Construction with Regolith Concrete

Construction Location Flexibility

Multi-axis print head

Curved wall tool path development

Images Courtesy of Dr. B. Khoshnevis, Contour Crafting, LLC for NASA NIAC

11 April 2016
3D Additive Construction Elements Using In-Situ Materials (Basalt)

Environmental Protection

Images Courtesy of Dr. B. Khoshnevis, Contour Crafting, LLC for NASA NIAC

Complex Tool Path Development Allows Interior Walls
Bench Top Test Results

Successful laser based fabrication of test materials and bench-top scale freestanding structures was achieved with several types of regolith simulant including:

- Black Point -1 (BP-1), Lunar Regolith Basalt Simulant – NASA KSC
- JSC-1A, Lunar Mare Simulant – NASA Johnson Space Center (JSC)
- NU-LHT-2M, Lunar Highland Type Simulant (2 Medium) – NASA USGS
- Hawaiian Basaltic Tephra from Mauna Kea Volcano, Hai Wahine Valley
- Standard White Construction Sand with 30% by weight added BP-1
- Cape Canaveral “Jetty Park” Beach Sand with 30% by weight added BP-1

Figure 2. Bench-top scale freestanding structures created by Swamp Works 3D Regolith Construction process: A) BP-1 Hollow Cone Structure; B) BP-1 Hollow Ogive Dome Structure
Phased Approach to Space Construction

- **CLASS I:**
  - Preintegrated, Hard Shell Module
- **CLASS II:**
  - Prefabricated, Surface Assembled
- **CLASS III:**
  - ISRU Derived Structure w/ Integrated Earth components

Credit: Scott Howe, JPL
Class I: Pre-integrated Construction

- Fully usable
- No assembly required
- Limited by payload size
Class II: Pre-fabricated Construction

- Assembled onsite
- Robust joints
- Replacable
- No size limit

Transformable Robotic Infrastructure-Generating Object Network (TRIGON)

TransHab (courtesy NASA)
Class II Execution: Robotic Assembly

Credit: Scott Howe, JPL
Class III: In-situ Construction

- Need up-front technology
- Onsite effort
- Unlimited resources
- Sustainable

Sinterhab

Sandbag domes (courtesy CalEarth)
Class III Concepts: 3D Additive Construction

7 DOF umbilical / material handling
ATHLETE limb
Print head hardware
ATHLETE tool grasp
Layering of printed material (print path shown in red)

Credit: Scott Howe, JPL
Class III Concept: Shells Structures

1. Ultraflex solar arrays
   - FACS production plant on pallet
   - ATHLETE mobility system
   - Airlock module w/ pallet

2. Partially printed shell, diagonal print pattern allows the printing of vaults without scaffolding

3. Printed regolith shell
   - Liner inflates after shell is completed
   - Airlock module / pallet
   - Additional modules can be placed for outpost

Credit: Scott Howe, JPL
Application: Printed Habitat Shells: “Sinterhab”

Credit: Scott Howe, JPL
Class III Concept: In-situ Assembly

- Modular panels, arches, beams printed on the ground
- FACS system
- ATHLETE mobility system
- In-situ printed paving blocks for lander pads
- ATHLETE can lift and manipulate panels into in-situ structure
- Modular archways and scaffolding assembled from in-situ printed panels

Credit: Scott Howe, JPL
Class III Concept: In-situ Assembly

Tilt-up construction
Support scaffolding
ATHLETE system
Partially constructed vault
Vault structure buried under loose regolith

Credit: Scott Howe, JPL
Asteroid Habitat Concept

– Microgravity Technology Demonstration: Stabilizing the surface of an asteroid that can be hollowed out for radiation protection of human habitats

Asteroid with powder regolith surface
Robotic mobility system placing grid of anchors
3D Automated Additive Construction technology hardens and stabilizes surface
Asteroid is partially hollowed out
Inflatable habitat inserted and inflated
Docking nodes, propulsion systems

Credit: Scott Howe, JPL
# Vision for AAC

<table>
<thead>
<tr>
<th>Time Frame (years)</th>
<th>Resource Utilization</th>
<th>Humans Off-planet</th>
<th>Automated Additive Construction Technology</th>
<th>Energy</th>
<th>Byproducts</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Terrestrial demonstration of regolith processing / separation; Extraterrestrial prospecting</td>
<td>Trips to Moon / Mars / asteroids</td>
<td>Demonstrate terrestrial 3D printing with sintering / melting, print landing pads / shelters</td>
<td>All systems Earth manufactured</td>
<td>Volatile collection demonstration</td>
</tr>
<tr>
<td>25</td>
<td>Harness bulk regolith; Test regolith separation in space; Mars cyclers for radiation shielding</td>
<td>Habitation / outposts on Moon/Mars</td>
<td>Autonomous construction with bulk in-situ resources; 3D construction of landing pads, shelters in space</td>
<td>Exporting solar cells from Earth; manufacture concentrators in-situ</td>
<td>In-space collection of water separation into constituent gasses</td>
</tr>
<tr>
<td>50</td>
<td>Autonomous materials processing into desired elements / compounds; Cu/Fe extraction</td>
<td>Colonies; financially self-sustaining industries off-planet</td>
<td>Partial self-replicating factories; habitats/structures made in-situ</td>
<td>Sustainable off-world energy sources: solar concentrators, photovoltaics manufactured in-situ</td>
<td>Limited off-Earth fuel production: hydrocarbon, oxygen</td>
</tr>
<tr>
<td>100</td>
<td>Resource independence; terraforming asteroids; enclosed lunar / Martian cities</td>
<td>Communities on Mars / Moon / asteroids</td>
<td>3D additive industry; silicon / biologically based self-replicating factories</td>
<td>Communities independent of Earth resources; harness off-planet resources to create energy sources and storage</td>
<td>Sustainable off-Earth fuel production</td>
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</tbody>
</table>
Centennial Challenge: 3D Print a Habitat

Solving the need for safe, secure and sustainable housing on earth and beyond.
Summary

• There are vast amounts of resources in the solar system that will be useful to humans in space and possibly on Earth
• Shelter for fragile humans will be required
• Space faring humans will need planetary bases which will require planetary surface construction
• New technologies are developing rapidly, allowing for robotic automated construction
• Much more work is needed before Planetary Surface Construction becomes viable, but *the first commercial space companies are emerging today*
• Government labs are already developing prototypes
• *It’s your future – make it happen*