

STATUS QUO

**NEW INSIGHTS** 

# HRS: Rover Technologies



 Rich research and development community of terrestrial mobile robots

Agency flagship Mars rover missions

### **PROBLEM/NEED BEING ADDRESSED**

Low cost rover development that supports searching for volatiles as part of the resource prospector mission

### PROJECT DESCRIPTION/APPROACH

- Develop and advance TRL of rover technologies, focusing on Resource Prospector mission
- Build and test prototype rover in FY15
- Advance TRL through test in FY16/17
- Develop new approaches to navigation, sensing and rover operations for high paced operations and short duration missions.

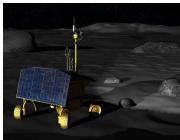
Add active suspension up to 8 cm (compared to passive suspension in MER/MSL

 Pace of planning up to 4/hr (compared to 1/sol in MER/MSL)



**QUANTITATIVE IMPACT** 

Develop rover and rover technologies to be infused into Resource Prospector mission and future surface missions





 NASA is developing a culture of Class D low cost, "high" risk missions (LRO, LADEE, small sat, etc). An opportunity exists to extend this into the rover regime that will be parallel to the existing flagship SMD Mars rover missions



# STATUS QUO

# **NEW INSIGHTS**

# HRS: Space Robotics Challenge



- Little autonomy in NASA robotics
- Humanoids that cannot fully function as assistants to crew
- Rovers are only robots prepared for pre-cursor missions

### PROBLEM/NEED BEING ADDRESSED

NASA humanoid robots need more autonomy for Mars-mission type scenarios

### PROJECT DESCRIPTION/APPROACH

- Redesign Valkyrie robot for sensing needs
- IHMC provides robust walking software
- Build 2 new Valkyrie robots
- Provide robots to US research teams through competitive bidding
- Administer Space Robotics Challenge as two-tiered, two-track competition
  - Virtual competition is tier 1, physical competition is tier 2
  - Robonaut 2 and Valkyrie will be competition platforms

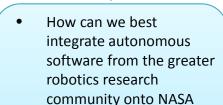
- More autonomous skill sets for mobile, dexterous robots
- Dual-arm manipulation while walking or climbing
- Handling of soft good items



**QUANTITATIVE IMPACT** 

To provide a complex humanoid platform for US research teams to test their advanced autonomy software





robotic platforms?





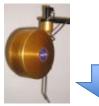
# Long, Thin 'Continuum' Robots for Space Applications



STATUS QUO

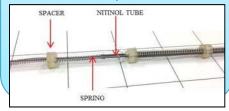
• Nature – tails, trunks, tentacles

- Tendril developed in a joint effort between Clemson University and NASA 2006
- Cottar Continuum Manipulator -Clemson
- CardioArm Carnegie Mellon 2008





- · Key understanding gained in earlier collaborative work with NASA enables fundamentally new research directions
- Clemson continuum laboratory has been developed over the past 15 years under funding from NASA, DARPA, and the NSF
- Team has gained significant expertise in software environments for real-time continuum robot operation



### PROBLEM/NEED BEING ADDRESSED

NASA needs the ability to remotely inspect tight areas in space vehicles, such as behind racks on ISS, inside payload containers, and beneath thermal blankets, or to perform robust manipulation / exploration within inaccessible regions of extra-terrestrial bodies

### PROJECT DESCRIPTION/APPROACH

- Conduct R&D of long, thin, continuous backboned or "continuum" robots to solve problems of interest to NASA
- Collaborate with JSC, JPL, and GSFC
- The proposed research has two high-level objectives:
  - Develop long thin continuum robots featuring capabilities significantly beyond the state of the art
  - Demonstrate the ability of new capabilities to transform application scenarios of particular interest to NASA
- The research plan is structured in 3 thrusts:
  - Evaluate of a set of design alternatives, down-selecting through prototypes and testing to final robot hardware
  - Empirical investigation of the ability of new robots to penetrate and investigate tight, narrow spaces
  - Research in grasping & manipulation with long thin robots
- Preliminary findings in FY14 have lead to discovery of a new approach and prototyping of a scaly membrane that expands and contracts in length and can be locked into a shape





- Completing 2<sup>nd</sup> year of NRI research in FY14
- Cost/Schedule: \$105K 2<sup>nd</sup> yr. / \$545K total over 5 years

Improved smoothness of motion

- Improved ability to attain predicted amounts and locations of bending
- Improved durability
- Increased response speed
- Improved ability to penetrate and maneuver within tight spaces
- Improve / Develop algorithms to predict and control bending behavior





Extend the state of the art to create robots with capabilities previously unattainable

### **Potential Applications:**

- NASA ISS, future exploration missions
- Homeland Security safe inspection of tight spaces such as inside cars
  - Agriculture & Env. Protection nondestructive robotic access to more remote environments
  - Medicine sensing and surgery in complex parts of the body
  - Industry novel approaches to constraint and manipulation

# A Novel Powered Leg Prosthesis Simulator for Sensing & Control Development



Current prosthetic leg devices have limited degrees of freedom or limited output capacity and can only be used for walking at low to moderate speeds No leg prostheses yet match the performance of a living leg, but a few are making strides toward the goal

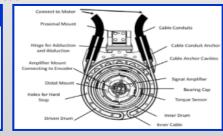
### PROBLEM/NEED BEING ADDRESSED

Designers of powered prosthetic legs, exoskeleton legs, & robot legs lack the means to quickly search the design space hardware and control systems for optimal solutions

### PROJECT DESCRIPTION/APPROACH

- Develop leg prosthesis simulator capable of applying specific model-predicted torques to both prosthetic & residual limbs of amputees and robot or exoskeleton legs
- Using a cable drive mechanism (Exo-Drive), the simulator will apply torque to both prosthetic and residual limb joints while an amputee or robot walks on a treadmill





- Collect kinematic, kinetic, elctromyographic, and metabolic data to develop a knowledge base that can be used to assess electromechanical prosthetic devices their control strategies
- · Demonstrate that with the correct control scheme, the simulator can enable amputees to regain normal gait
- Phase 1 (FY13-15) design/build Transtibial Prosthesis Simulator; program model-based control & sensing; evaluate on walking transtibial amputees or NASA Robonaut
- Collaborate with JSC Exoskeleton team on wearable robotics
- Completing 2<sup>nd</sup> year of NRI research in FY14
- Cost/Schedule: \$246K 2<sup>nd</sup> yr. / \$1.176 M total over 5 years

### The simulator will:

QUANTITATIVE IMPACT

- Allow simulation of different prosthetic/ robotic hardware sensing & control schemes
- Provide useful test platform for NASA robotics
- Allow NASA to test Exo device and Robonaut legs with different control
- Allow NASA to characterize human-machine performance

### The Exo-Drive development will provide:

- Antagonistic control, cable termination, tendon-life, and torque/force sensing data relevant to NASA's new Exo design & Robonaut's hands
- Kinetic and kinematic data that will enable creation of new prosthetics that allow amputees to regain a normal gait, Improve ambulatory speed, and Improve stability



Provide prosthetics and robotics designers the simulation tools and data necessary to allow creation of prosthetics / robotic limbs that more closely imitate the motion of the human leg



Simulator with amputee volunteer & prosthetic leg



foot prosthesis, uses inertial measurements & torque sensors to make informed decisions on the control of a series-elastic actuator that propels the user forward with each step

PowerFoot - the 1st robotic ankle-

**New Sensing Technology:** Proprio Foot - quasi-passive ankle-

determine the wearer's phase in the

**More Sophisticated Actuation:** 

foot device that uses sensors to

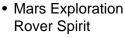
gait cycle



# Long-range Prediction of Non-Geometric Terrain Hazards for Reliable Planetary Rover Traverse



 Stereo Cameras and LIDAR sensors excel at sensing geometric obstacles, but fail to detect hazards like weak or slippery terrain



Honeybee Robotics percussive drive mounted on NASA K10 rover



- Recent research into sensing of non-geometric terrain properties takes a "drive-by-feel" approach, where terrain properties are measured by driving over the terrain and comparing observed motion to actuation effort
- The measurements are correlated with terrain appearance to predict upcoming hazards
- While effective at short range, this approach is indirect and cannot measure terrain properties without wheel-terrain

### PROBLEM/NEED BEING ADDRESSED

NASA needs better ways of detecting non-geometric terrain hazards such as soft soil, because they are mission-enders for autonomous ground vehicles on Earth and beyond - *Spirit* was mired in soft soil on Mars and *Lunokhod* got stuck in regolith on the Moon

PROJECT DESCRIPTION/APPROACH

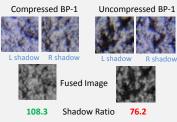
### FY14

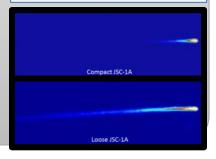
- Investigate use of multiple sensing modes for short & long range terrain property measurement
- Stereo visual odometry and wheel odometry to determine instantaneous slip on slopes
- Standoff microscopy to reveal surface structure and particle distribution to infer compaction
- Use laser to heat soil in front of rover and thermal imaging to view the heat pattern to infer the level of compaction

### FY15

- Develop self-supervised learning software that can map multimode long-range sensor data to terrain properties
- Develop receding horizon contingency planning s/w that applies learned models of vehicle-terrain interaction to maintain stability and safety
- Completing 2nd year of NRI research in FY14
- Cost/Schedule: \$249K 2<sup>nd</sup> yr. / \$761K total over 3 years

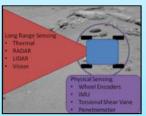






- Improve ability to determine slippage on slopes utilizing highfidelity high-frequency visual odometry (goal 97% accuracy)
- Develop methods of predicting loose soil at long range (previous methods = 0; goal = 2 to 3 methods)

**QUANTITATIVE IMPACT** 



- Develop method for robots to perceive and react to terrain hazards before engaging
- Overcome one of the major barriers to infusion of automated safety features in passenger cars - hazard assessment
- Fast, robust, predictive assessment of hazard will enable driving, working and exploring near the limits of machine capability





# Active Skins for Simplified Tactile Feedback in Robotics



- Tactile sensing has been a topic in robotics for over 30 years
- Effective grasping of soft deformable objects, (including people in medical contexts) requires knowledge of the forces the robot is applying
- Inexpensive Force Sensitive Resistors (FSR) have been around for over a decade and have been used for tactile sensing, but no one has yet achieved highly integrated sensor systems



The fundamental breakthrough required to provide sense of touch is development of tactile sensing systems that address everything from the sensors to the manufacturing and cost to the integration (wiring, control, etc.)

Robotic hands have made significant progress over the last few years, but lack

high- density tactile sensors Build on existing successes in:

Sensor development
Micro-manufacturing
Miniaturization of electronics
More rigid polymers (a)
Elastomers combined w/ metal (b)
Highly stretchable elastomer and carbon
nanotube networks (c)



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### **PROBLEM/NEED BEING ADDRESSED**

Robots working alongside people or interacting with us require a *sense of touch* to safely and effectively interact with us and to handle soft, fragile, or deformable objects (often designed only for human use)

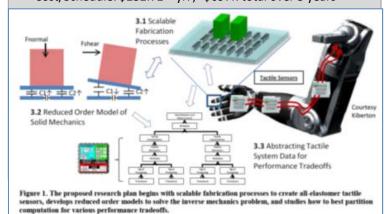
### PROJECT DESCRIPTION/APPROACH

The primary focus of this research is on development of a *tactile* sensing system for dexterous manipulation using:

- scalable micro-fabrication methods,
- reduced order modeling of elastomer deformations, and
- distributed computation in embedded CMOS

The goal is to produce soft, conformable, robotic skins with active embedded sensors and processing that will allow a robot to easily acquire and interpret tactile data

- · Completing 2nd year of NRI research in FY14
- Cost/Schedule: \$232K 2<sup>nd</sup> yr. / \$697K total over 3 years



### **Target specifications:**

**QUANTITATIVE IMPACT** 

GOAL

PROJECT

- Force sensitivities in 3 axes of 1 mN to 1 N
- Dynamic range of 1000:1 to cover a wide range of manipulation tasks
- Thickness under 500 mm
- Bandwidth for a single tactile pixel of approximately 1 kHz
- Minimum spatial resolutions of 1 sensor per millimeter
- Power < 10 mW per fingertip</li>

Tactile data will be especially important for 21st century robots that interact with soft, deformable objects, including people



- Goal is to create soft, conformable, robotic skin with active embedded sensors and processing and share the advances
- These active skins will be combined with future collaborations to integrate large array touch sensing on industrial, medical, and home-care robots
  - Findings from this project will be periodically posted to iMechanica.org to expose the mechanics community to state-of-the-art tactile sensing for robotics
- Upon completion, the PIs will write a review article summarizing their findings
- Short videos will be posted to YouTube for broader public education as well



STATUS QUO

**NEW INSIGHTS** 

## NRI Grant: Actuators for Safe, Strong, & Efficient Humanoid Robots



- Existing actuator knowledge has significant deficiencies
- Commonly stated that electromechanical actuators have low power & low torque/mass ratios compared to hydraulics or pneumatics
- Pneumatics often characterized as having a high torque density, but are more challenging to
- Most actuator components have not been tailored for specific joint function
- Current approach is to select the equipment believed to best fit a balance of torque, speed, efficiency, & control requirements
- There has been little research on the optimization of an entire actuator electric drive (power converter, electric machine, and control)
- and high-bandwidth power electronic converters make traditional machine design practices highly conservative This team has developed design tools for several classes of electric machine/power converter systems which are not based on traditional design practices, but are instead based on formal and rigorous

New materials, new control strategies,

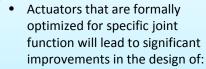
multi-objective optimization techniques Purdue successfully optimized, constructed, and tested several machines using this approach, including a permanent magnet (PM) elbow actuator motor designed as a replacement for one on NASA's Robonaut 2

### PROBLEM/NEED BEING ADDRESSED

Current robotic actuators are not efficient enough to meet the requirements of future lightweight robots, exoskeletons, and prosthetics.

### PROJECT DESCRIPTION/APPROACH

- Rigorously address technical issues associated with multi-objective optimization of actuators used in humanoid robots to provide means to design actuators that are on the boundary of theoretically achievable performance
  - Provide a rigorous approach to custom design of actuators tailored to specific joint function
  - Integrate the multi-domain models of power converters, controls, joint load profiles, and electric machines
  - Use formal multi-objective optimization to determine the boundaries of achievable performance for several existing and novel actuator drive topologies
  - Apply & experimentally validated results using the knee joint of NASA's Robonaut 2 as a primary design example
- In parallel, investigate new classes of electric machinery for actuators, including:
  - Reluctance & permanent magnet machines
  - Magnetic gearbox assemblies
  - Lundell (claw-pole) motors
- Finishing 2<sup>nd</sup> year of NRI research
- Cost/Schedule: \$165K 2<sup>nd</sup> yr. / \$497K total over 3 years



- Humanoid Robots
- Exoskeletons
- Prosthetic Joints
- Potential benefits include:
- Increased Strength
- Increase Endurance
- **Mass Reduction**





- Provide NASA with methods to custom-design robotic actuators that are on the boundary of theoretically achievable performance
- New projects based upon actuator design will be integrated into both undergraduate and graduate courses, effectively transferring the knowledge to many generations of students

GOAL **PROJECT** 

**QUANTITATIVE IMPACT** 



# NRI Grant: Manipulating Flexible Materials



Prior work by the PI has demonstrated that using force and tactile sensing to localize flexible materials is a feasible approach for small-scale manipulation problems
 However, it is difficult to scale the

- However, it is difficult to scale the approach up to large problems because of the challenges involved in developing a haptic model of what the material is expected to "feel" like
- The problem is that it is hard to model flexible materials analytically and it can be difficult to gather a sufficiently large amount of training experience to train an accurate model



- Sparse coding has produced state-ofthe art results in speech, text, and image classification domains
- Similar results can be achieved in manipulation where it is important to learn from very few labeled examples
- PI lead dev of R2 control & autonomy and is uniquely qualified to develop these applications on R2
- In FY13 the team developed a novel sensor arrangement using the GelSight sensor

### PROBLEM/NEED BEING ADDRESSED

Manipulating flexible/deformable objects is a key challenge in developing robots to work with humans in manufacturing & space (NASA EVA repair often requires manipulation of thermal blankets to access equipment

### PROJECT DESCRIPTION/APPROACH

- Use force & tactile sensing to localize flexible materials
- Develop and test 2 ideas representative of NASA applications:
  - Use sparse coding to enable the robot to learn a set of haptic basis vectors that encode "micro-scale" haptic structure common to all objects from easy-to-obtain unlabeled data
- Use techniques from robot localization & mapping to create haptic models of objects based on unstructured training data
- Develop applications on Barrett arm/hand system
- Aspects of the applications will also be tested using Robonaut 2 at GM
- Finishing 2<sup>nd</sup> year of NRI research
- Cost/Sched: \$254K 2<sup>nd</sup> yr. / \$756K total over 3 years



How does our algorithm work?



- Enable dexterous robots to perform work that only humans can currently perform
  - Robots could perform dangerous EVA tasks with thermal blankets, cable routing, etc.
  - Potential of large impacts on manufacturing flexible materials & deformable parts, which are common in US manufacturing, but where there is no automated assembly as yet



**QUANTITATIVE IMPACT** 

GOAL

- Make it easier & less expensive to create haptic models for use by robots
- Make data sets & software publicly available to the research community
- Disseminate tactile data sets that can be downloaded and used by robot manipulation researchers everywhere
- Plan to make ROS packages available that other researchers with access to a properly configured Barrett arm/hand system can use to replicate our results





# Whole-Body Telemanipulation of the Dreamer Humanoid Robot on Rough Terrains Using a Hand Exoskeleton



Current manufacturing robots are expensive and limited to preprogrammed tasks. Most robots are designed and built for a specific task and can not perform the tasks of other robots. There are no manufacturing robots that are truly dexterous and capable of performing many dissimilar tasks

### PROBLEM/NEED BEING ADDRESSED

NASA currently lacks a robust method of remotely controlling (tele-operating) the whole body of a humanoid robot, especially over rough terrain

### PROJECT DESCRIPTION/APPROACH

- Design an anthropomorphic hand exoskeleton, to be worn by a user, to provide natural control of a humanoid robot and force feedback to the user
- Integrate previous efforts in whole body manipulation and control with new efforts in pHRI to efficiently control mobile humanoid robots in manufacturing settings and on rough terrains as follows:
  - Develop a whole-body compliant control & modeling paradigm for the humanoid robot *Dreamer*
  - Design and build novel hand exoskeleton for telemanipulation of *Dreamer*
  - Develop a computational infrastructure for transferring the exoskeleton control skills to telemanipulation of Dreamer in complex & changing manufacturing environments
- Collaborate with JSC on whole-body tele-manipulation
- Completing 2nd year of research in FY14
- Cost/Schedule: \$345K 2nd yr. / \$1.38M total over 4 years

QUANTITATIVE IMPACT

PROJECT GOAL

- Provide cost effective, intuitive, natural means for people to control mobile dexterous robots
- Enable small & medium size manufacturing businesses to become competitive worldwide
- Revive and improve the state of manufacturing in the U.S.



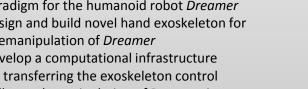
### Develop a control framework for telemanipulation of low-cost mobile & dexterous robots, keeping humans at the center of the control loop by retargeting low-level exoskeleton gestures to sophisticated humanoid skills

- Provide NASA with a robust, natural method of tele-operating humanoid robots via an exoskeleton hand control Create interdisciplinary environment enabling:
- Education, training, and co-advising of grad & undergrad students
- Target outreach activities to underrepresented groups in science and engineering in Texas and Maine 185



Physical human-robot interaction (pHRI), an emerging technology, is the study of biological principles governing human motion and using them to realize mechatronic technologies for robotics. A general theoretical & computational framework to model & control pHRI systems has not yet been consolidated.

The team recently developed & implemented a Whole-Body Compliant Control Architecture (WBC) in the Dreamer humanoid robot, the Willow Garage PR2 robot and R5 demonstrating feasibility of endowing whole-body compliant skills to mobile dexterous robots.



# Toward Humanoid Avatar Robots for Co-exploration of Hazardous Environments



Today's robots are typically fully tele-operated, placing a large burden on the operator, or have autonomy that is opaque, leading to automation surprises. Today's best humanoids still fall over from slight pushes and cannot walk on even slightly rough ground without a high precision



### PROJECT DESCRIPTION/APPROACH

- Existing open source robotics software libraries will be extended to make them more transparent, directable, and predictable in the avatar system.
- Demonstrate alternate approach to pure tele-operation or pure autonomy
- Demonstrate feasibility of using human-humanoid avatar robot teams for co-exploration of hazardous environments
- Improve humanoid motion planning in complex, dynamic, and unstructured environments
- Development will be focused on NASA's R5, which is available to the team through an existing cooperative agreement with NASA.
- Completing 2<sup>nd</sup> year of research in FY14
- Cost/Schedule: 1st yr. = \$992K, 5 yr. total = \$5.78M



### PROBLEM/NEED BEING ADDRESSED

Robots lack the mobility and reliability required to safety interact with humans and other robots, and lack the coordination required to ambulate to and do useful work in hazardous environments

- Improved balance algorithms

**QUANTITATIVE IMPACT** 

PROJECT GOAL

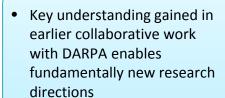
- Improved walking algorithms
- Ability to move over unstructured environments such as the scene of an accident or the surface of another planet or moon





Demonstrate feasibility of using humanhumanoid avatar robot teams for coexploration of hazardous environments using R5 as a testbed

# model of the surface









# NRI Grant: Building the Robotic Commons



# STATUS QUO

- Until recently, robotic software and hardware development has been an extremely expensive and time consuming effort to undertake
- NASA had to write all their own software from scratch for each new form of robot



- Robot Operation System (ROS) open source libraries and tools to help software developers create robot applications
- Gazebo Project a 3D multi-robot simulator with dynamics. It is capable of simulating articulated robot in complex and realistic environments <a href="http://gazebosim.org/">http://gazebosim.org/</a>
   Willow Garage PR2 developed PR2 robot, a robotics research and development platform that lets
  - Willow Garage PR2 developed PR2 robot, a robotics research and development platform that lets developers innovate right out of the box without building hardware and software from scratch

### PROBLEM/NEED BEING ADDRESSED

Support the Open Source Robotics Foundation (OSRF) in continued development of ROS, Gazebo, and other open source robotics software utilized by NASA to reduce software development costs

### PROJECT DESCRIPTION/APPROACH

- Continue development of Robot Operating System (ROS), currently used by a number of NASA robotics projects
- Continue development of Gazebo robot simulator
- Continued development, distribution, and adoption of open source software for use in robotics research, and education
- Work with JSC, JPL and ARC on robotic s/w –ROS has recently been integrated with R2 space legs, R5, Centaur 2
- Completing 2nd year of research in FY14
- Cost: 2nd yr. = \$334K, 3 yr. total = \$1M





- Improve capabilities and performance of open source ROS software
- Improve Gazebo robotics simulator capabilities
- Gain new insights and capabilities for disaster response robots



### Advance the overall capabilities and performance of ROS and Gazebo for use by NASA's robotics projects

 Advance existing state of the art in robotics for disaster response

# PROJECT GOAL

**QUANTITATIVE IMPACT** 



### BAA Grant:

# Representing and Exploiting Cumulative Experience with Objects for Autonomous Manipulation



• Fixed Automation - Most robots are designed and built for a specific task and can not perform the tasks of other robots

### Adaptive Controls

- Gain tuning

STATUS QUO

**NEW INSIGHTS** 

- Self calibration
- Dynamic identification

### Autonomous grasping

- RFID tags
- Fixed jigs



- Vast amounts of sensor data are now available on hands.
- Data includes motion, force, and other proprioceptive information
- Data also includes observation of external objects, tools and the environment.
- A control basis can be formulated with online experiences
- Grasping control can be associated with objects, used as a good start, and then further refined.
- Robots can share knowledge.

### PROBLEM/NEED BEING ADDRESSED

Robots must currently be designed for and then programmed for each specific task.

### PROJECT DESCRIPTION/APPROACH

- Develop and prove through testing a new approach to robot learning.
- The low level control basis approach allows simple skills to be put together for more complex actions.

### Key Challenges

- Task generality, through fusion of many types of sensing
- Robot generality, with object centric approach

### • Team

- PI is the leader in the field of autonomous manipulation
- Small team, mainly with graduate students
- Infusion through the Robonaut system on ISS, taking ideas through software development to flight on a fast pace.
- NRC requested more autonomy for NASA's Robonaut system

### Mission Impact

- Reduce operations costs by adding new tasks quickly.
- Provide a "caretaking robot" to be left behind on human tended spacecraft at NEAs, L2 or the moon.
- Terrestrial Impact

**QUANTITATIVE IMPACT** 

PROJECT GOAL

- Direct connection to manufacturing
- Medicine, disaster response, DOD



Advance the ability of robots to achieve the general ability to perform multiple tasks, get better through experience, develop new abilities, and share them with other robots.

