Robotics State of the Art Report

NEXT FY01

September 28, 2001

Space Robotics Assessment Functionality Metrics

Liam Pedersen (NASA Ames), David Kortenkamp (NASA JSC), Illah Nourbakshk (Carnegie Mellon University)

September 28, 2001

Levels of autonomy

- *Direct tele-operation*: operators in high-bandwidth, low latency contact (astronauts at worksite or nearby).
- *Supervised tele-operation*: Several communications cycles routinely required for task. Each command cycle operators upload detailed command sequence, responses to failures or deviations from plan are severely limited.
- *Highly autonomous*: Robot only infrequently needs to contact human operators to deal with problem situations, and multiple operations are routinely accomplished between each communications cycle. Operators can specify high level goal, onboard software plans (and re-plans) sequence of actions to attain goal.

Surface Exploration Scenario:
Most tasks can be accomplished by direct tele-operation given suitable engineering resources but no new technological developments. Furthermore, a human presence on Mars is unlikely in the near term. *In general, unless specified in the metric, we assume at least supervised teleoperation*.

In-Space Construction Scenario:
Many activities cannot be accomplished without autonomy, regardless of the presence of on-site astronauts or operators in high bandwidth, low latency communications.

Robustness

- *Fragile:* Robot commonly (> 50%) fails to achieve task at desired performance level in a realistic integrated test environment. Failures occur due to lighting variations, shadows, interactions with other subsystems, mild changes in perceived environment due to robot motion and small deviations (2X) from design specifications of task parameters (such as rock mass or size). This level is insufficient for mission systems and therefore is not considered.
- *Nominal robustness:* Robot usually achieves task at desired performance level to accomplish mission under nominal circumstances in a realistic integrated test environment (TRL6). Sufficient for non-mission critical tasks.
- *Mission critical robustness:* Robot always accomplishes task at desired performance level under nominal circumstances in a realistic integrated test environment (TRL 6), well characterized performance envelope with guaranteed reliability within that envelope. Performance degrades gracefully nominal mission design envelope exceeded. Sufficient for mission critical tasks.

For a capability (as measured by a metric) to be considered available at the very least nominal robustness must be demonstrated.

In-Space Assembly, Inspection and Maintenance Scenario

In-space assembly, maintenance and inspection functionalities. Functionalities are those robotic capabilities necessary to perform various missions. Each functionality has qualitative metrics that will be used to assess the state-of-the-art and project future capabilities. The metrics are linearly ordered from easiest to achieve to hardest to achieve.

1. Assembling structures

1.1 Transporting components

1.1.1 Qualitative Metrics

- Payload capture
    1. Grasp payload attached to same structure as robot
    2. Grasp payload held by another robot attached to structure
    3. Grasp payload that is free flying via teleoperation
    4. Grasp payload this is free flying autonomously
- Moving payload autonomously from initial position to goal position
    1. Move a payload to the goal with known information about fixed structure geometry
    2. Move payload to the goal with only partial information about the structure geometry
    3. Move a payload that has multiple degrees of freedom and complex geometry, avoiding collisions between all payload parts and structure.
    4. Move a payload while taking into account dynamics of moving objects

Feature: Plan paths that minimize energy consumption or delta-vee

Feature: Plan coverage patterns for a 3D structure

- Soft payload capabilities (autonomous)

1. Robot motion minimizing acceleration
2. Payload motion minimizing payload forces
3. Sensing payload forces in real time and minimizing sensed forces
4. Dynamic damping of flexible payloads

Feature: Handle extreme-lightweight structures (e.g. gossamer structures)

- Level of sophistication for avoiding collisions

1. Emergency stop before hitting an obstacle.
2. Efficiently avoid collisions by changing course early

3. Avoiding collisions by taking into account moving objects and their future positions
4. Moving the payload directly to avoid collisions

1.2 Mating large components

1.2.1 Qualitative Metrics

- Attaching to payload and structure locations (autonomous)
    1. Unable to use visual markers
    2. Able to use special-purpose visual markers to go to a payload or structure location
    3. Able to visually go to the payload or structure without need for special markers
    4. Able to visually go to a moving payload
- Positioning of payload (autonomous)
    1. Estimating position based on flight trajectory
    2. Position determination of the payload relative to a sub-structure
    3. Position determination relative to the whole orbital structure using visual markers
    4. Position determination relative to the whole orbital structure using multiple measurement strategies for redundancy
- Placement and mating

1. Rudimentary assembly of one or more basic elements
2. Complex assembly of basic components including varying attachment orientations and multiple components
3. Rudimentary assembly of complex components including components with three or more attachment points, large mass, or flexible nature
4. Complex assembly of complex components

1.3 Making connections

1.3.1 Qualitative Metrics

- Grasping connectors
    1. Connector already attached to robot end-effector
    2. Robot gets connector from fixed location
    3. Robot grabs free-floating connector
- Classes of connectors
    1. Robot friendly connectors with sensory tags
    2. Robot friendly connectors without sensory tags
    3. Current EVA electrical and fluid connectors
    4. Small, orientation sensitive connectors
- Classes of conduits
    1. Rigid, yet pliable

    2. Flexible
- Classes of tie-downs

1.4 Assembly sequence planning and execution

1.4.1 Qualitative Metrics

- Ground-based planning and sequencing

1. Large robot staff. Robot operations personnel generate detailed sequence to accomplish tasks, possibly rejecting some tasks that don't fit resource & operational constraints.
2. Task plan generated from CAD drawings of structure and input from structure engineers. Robot ops personnel add robot-specific details and any additional tasks to plan.
3. Task plan generated from CAD drawings is nearly complete. Robot ops personnel add navigation and manipulation trajectories.
4. All planning and sequencing is done from CAD drawings and engineering input. Minimal robot operations.

- On-board execution

1. Plan is a detailed, time-stamped sequence of low-level commands. Behavior entirely defined by input; system's default response to problems is to halt.
2. Plan allows flexible time specification and contingencies, enabling a family of behaviors.
3. Planner allows a prioritized list of tasks, with constraints among them.
4. Very high-level goal commanding (e.g., assemble this structure). System responds to opportunities and recovers from most faults. System adapts to robot degradation.

2. Inspecting structures

2.1 Mobility for inspection

2.1.1 Qualitative Metrics

- Localization
    1. No localization
    2. Localization with respect to internal sensors
    3. Localization with respect to global positioning sensors
    4. Localization with respect to structure
- Real-time control
    1. Stop when within proximity of an obstacle
    2. Steer around an obstacle
    3. Plan a path around an obstacle
    4. Integrate obstacle avoidance with path planning
- Path planning
    1. No path planning – only straight line navigation
    2. Point to point path planning

3. Path planning in three-dimensions from a static model
4. Incremental path planning in three-dimensions using sensor information

2.2 Routine, comprehensive inspection

2.2.1 Qualitative Metrics

- Types of structures
  1. Regular, flat structures (e.g., solar panel)
  2. Irregular, flat structures
  3. Regular, convex structures (e.g., module hull)
  4. Irregular, convex structures
  5. Complex, 3-D structures (e.g., truss)
- On-board planning and execution
  1. Robot given detailed sequence of inspection path. Response to problems is halt.
  2. User selects inspection area with robot-planned coverage path. Automatic work-arounds for many problems
  3. User selects multiple inspection tasks and robot prioritizes and accomplishes those tasks responding to novel situations
  4. High-level inspection tasks with little human input. Robot adapts to degradations in performance
- Data analysis
  1. No data analysis, all sensor data stored or sent in raw form
  2. "Mosaicing" of sensory data to provide continuous view; no analysis
  3. Autonomous detection of clearly defined and modeled anomalies
  4. Autonomous detection of anomalies by sensor comparison against previous, nominal inspections

2.3 Anomaly-driven inspection

2.3.1 Qualitative Metrics

- Types of structures
  1. Regular, flat structures (e.g., solar panel)
  2. Irregular, flat structures
  3. Regular, convex structures (e.g., module hull)
  4. Irregular, convex structures
  5. Complex, 3-D structures (e.g., truss)
- Types of anomalies
  1. Visually distinct anomaly with prior knowledge by the robot
  2. Leak that cannot be detected visually
  3. Visually distinct anomaly without prior knowledge by the robot
  4. Comparison of "before" and "after" pictures
- Actions at the anomaly site

1. No action taken
2. Station-keeping such that anomaly is continuously monitored
3. Approach anomaly for closer look
4. Attempt simple repairs or stop-gap measures

3. Maintenance of structures

3.1 Change-out of components

3.1.1 Qualitative Metrics

- Identifying the component
  1. Visual (active or passive) markers
  2. No special markers
  3. Ability to identify components that are damaged (discolored, bent, etc.)
- Grasping the component
  1. Special purpose end-effector with special purpose handle
  2. Pre-designed connection handle with general purpose end-effector
  3. Ability to grasp handle that is damaged
  4. No pre-designed connection handle
- Inserting new component
  1. No external sensing of component or insertion path
  2. Visual sensing of insertion path
  3. Force accommodation while insertion occurs

3.2 Accessing obstructed components

3.2.1 Qualitative Metrics

- Opening panels/covers
  1. Rigid, undamaged panel with robot-friendly handle
  2. Rigid, undamaged panel with EVA-friendly handle
  3. Rigid, damaged panel
  4. Soft attached blanket with robot friendly handles
  5. Soft, attached blanket with EVA-friendly handles
- Removing debris
  1. Removing loose debris
  2. Removing attached debris
  3. Untangling wires
  4. Bending metal parts

3.3 Troubleshooting and diagnosis

3.3.1 Qualitative Metrics

- Ground-based troubleshooting
- On-board troubleshooting

4. Human EVA Assistance

4.1 Teleoperation of EVA robots

4.1.1 Qualitative Metrics

- Teleoperation mechanism
  1. Hand controller and direct viewing
  2. Hand controller and video from robot
  3. Hand controller with stereo video feedback
  4. Hand controller with force feedback
  5. Telepresence capability (human motion tracking and head-mounted stereo display)
- Situation awareness
  1. No additional situation awareness
  2. Overlays on top of video and/or some non-video sensor display (e.g., forces)
  3. Force feedback when near collision
  4. Graphical reconstructions of the workspace to show information not available through video
  5. Predictive displays tied to robot simulations
- Communication from robot
  1. Raw telemetry
  2. Filtered telemetry
  3. Internal state information
  4. Predictive and explanatory information

4.2 Monitoring of human EVA using robots

4.2.1 Qualitative Metrics

- Visual servoing
  1. Servoing to target when it is directly in view
  2. Servoing while avoiding obstacles
  3. Servoing through changes in viewpoint and lighting
  4. Reacquiring target after occlusion
- Video archiving
  1. Pointing camera at fixed location

2. Responding to simple voice or operator commands for camera position
3. Automatically moving camera to avoid occlusion
4. Automatically moving camera to get best view angle based on task being performed

4.3 Site preparation and clean-up

4.3.1 Qualitative Metrics

4.4 Human-robot teaming

Qualitative Metrics

- Human-robot communication
  1. Text-based commands entered using keyboard or mouse
  2. Low-level voice commands (e.g., stop, faster, move right, etc.)
  3. High-level voice commands, including referents (e.g., pick up that)
  4. Multi-modal communication (e.g., integration of speech and gestures or speech and graphics tablet)
  5. Dialogue with human about goals and actions
- Sensing of humans
  1. Generic obstacle avoidance and safe movement
  2. Tracking of humans in work environment
  3. Tracking of human body parts (e.g., gestures)
  4. Recognition of humans and their activities
  5. Sensing of self-collision (robot limbs colliding with other robot limbs)
- Gesture recognition
  1. Simple, static gestures
  2. Dynamic gestures
  3. Gestures linked to natural language for grounding of symbols
- Physical interaction
  1. Holding objects (light, tool, cable) for human
  2. Handing objects to human
  3. Taking objects from human
  4. Carrying/rescuing human

Planetary Exploration Scenario

Mobility Autonomy

Mobility autonomy for surface exploration consists of determining the robot's location, defining a goal location (in absolute coordinates or relative to a visible object), and planning and traversing a path to the goal location while avoiding unexpected obstacles. Mobility autonomy also consists of planning and executing a coverage pattern and integrating sensor readings to form a map.

This Mobility Autonomy analysis focuses on non-inflatable wheeled rovers because this locomotion modality covers the richest set of fielded systems from which the most confident forecasts of future competence may be generated.

Qualitative Metrics

- Localization
    1. Roughly localize using dead reckoning and inertial sensing
    2. Localize with respect to local pseudolites
    3. Track nearby landmarks to improve small-scale localization
    4. Localize with respect to orbital data, using landmarks visible from orbit (such as skyline features)
- Mapping
    1. Form local terrain maps, registering data sets naively (using pose from localization system)
    2. Improve registration by matching features in overlapping data sets
    3. Fusion from multiple data sources, including orbital data
    4. Global mapping

        a. **Feature:** Compressing and enhancing maps using automatic feature extraction
- Terrain assessment
    1. Detection of danger zones (e.g., obstacles and drop-offs) in the immediate vicinity, allowing the robot to stop before a collision
    2. Detection of danger zones in a neighborhood up to a few meters from the robot
    3. Detect finer traversability distinctions than danger/no danger (e.g., estimate energy required to move through different areas)
    4. Resolve large traversability features such as boulder fields in regions with size up to kilometers (e.g., from a hill-top view)
- Real-time control
    1. Stop before entering a danger zone (emergency stop)
    2. Steering in response to last-minute detection of danger zones up to a few meters away (this complements path planning, which is typically slower)
    3. Steering optimization in response to last-minute detection of fine distinctions in local traversability (steering through terrain that is not just safe, but easy)
    4. Take into account dynamics during high-speed rover motion
- Path planning
    1. Plan point-to-point trajectories
    2. Operate with partial terrain data
    3. Perform efficient incremental replanning as new information becomes available
    4. Plan paths which keep landmarks in view, and which do not require better localization than the rover can provide

        a. **Feature:** Plan coverage patterns in addition to point-to-point trajectories
- Visual servoing
    1. Move directly to a target which is in view throughout the motion
    2. Servo while avoiding obstacles
    3. Ability to track target through gross viewpoint and moderate environment condition (such as lighting) changes
    4. Integrate with path planning in order to reach more distant targets

        a. **Feature:** Robust target reacquisition (e.g., after moving away and coming back, or after target is temporarily occluded by an obstacle)

Quantitative Metrics

- **Distance traversed metrics.** We assume that the rover is told to move to a position through terrain known only from orbital imagery. The "distance traversed" is the straight line distance between the rover's position and the commanded position.
  - Mean distance traversed between mission-ending mobility failures. A corresponding metric for fielded systems is "Total distance autonomously traversed".
  - Mean distance traversed between failures which require operator intervention. A corresponding metric for fielded systems is "Longest distance between operator interventions".
  - Mean distance traversed per sol. This is a measure of speed which does not take into account failures which require operator intervention. We assume that the robot travels for 3 hours per sol (roughly half of the time during which there's a useful level of solar power).
- **Number of targets visited metrics. [maybe move to sample manipulation?]** By "visiting" a target, we mean moving to a precise position relative to the target to enable detailed study. We assume that targets are visually identifiable features specified by operators in the context of a map generated from the rover's sensor data, and that they are spaced so that the rover can follow a path that reaches a target every 5 meters.
  - Mean number of targets visited per operator intervention. This number may be less than one (e.g., Sojourner typically took three uplinks to servo to a target and receives a score of 1/3). A corresponding metric for fielded systems is "Largest number of targets visited between operator interventions".
  - Mean number of targets visited per sol. This is a measure of speed which does not take into account failures which require operator intervention. We assume that the robot seeks targets for 3 hours per sol (roughly half of the time during which there's a useful level of solar power).
- **Mapping and localization accuracy metrics.** For each measurement below, the metric of interest is the standard deviation of the measurement error.
  - Position error of self relative to object in view. We report worst case error, when the object is at the edge of the sensor footprint.
  - Position error of self relative to global orbital map

Mobility Mechanism

Mobility mechanism is the physical implementation of the mobility system. This means the configuration of legs, wheels (non-inflated and inflated), tracks, or other mechanisms to move the robot over a terrain. It also consists of the suspension, motors, transmission and center of gravity. These factors affect the kinds of obstacles that a rover can safely traverse over, the steepness of a slope it can navigate, the stability and location of the platform for sensing and manipulating and the maximum speed and power requirements. Mobility mechanism also includes mechanism and physical sensing for proprioception and terrain assessment. Mechanism design can be critical to the detection of boundary conditions for chassis stability before irreversible instability ensues. Less conventional mobility approaches such as flying (balloons or airplanes) and rappelling are also included in this functionality, but will not be a primary focus of this report.

Qualitative Metrics

- Chassis Stability Safeness
  1. Static stability within kinematic configuration space
  2. Dynamic stability within control envelope
  3. Self-righting recovery from limited upset conditions
  4. Self-righting recovery from all upset conditions

- Chassis Adaptability/Reconfigurability for Terrain Negotiation
  1. Passive reconfiguration via underactuation

    2. Active joint reconfiguration
    3. Active CG control
    4. Locomotion modality switching (e.g. from rolling to walking)
- Traversal Competencies: for each terrain class, 0=unable to traverse; 1=able to traverse partially; 2=able to traverse competently
    1. Hard flat surface (e.g. tundra)
    2. Soft flat surface (e.g. sand)
    3. Confined spaces
    4. Stream bed
    5. Boulder/Talus field
    6. Dune
    7. Liquids
    8. Cliff faces
- Mechanism Redundancy and Accomodation of Failure
    1. Design overactuation for redundancy
    2. Locomotion with partial motor failures
    3. Locomotion with partial joint failures
- Mechanism Longevity Design
    1. Wear-designed components (e.g. clutches, brake pads, brushes, etc.)
    2. Low-wear components (e.g. magnetic bearings, low-friction motors, etc.)
- Energy Efficiency and Power Considerations
    1. Negative work is performed by mechanism
    2. Negative work is avoided by mechanism
    3. Mechanism power regeneration
    4. Resonant mode use
- Environmental Isolation
    1. Basic thermal protection of key thermally sensitive components
    2. Basic dust protection of key moving parts
    3. Complete environmental isolation of mechanism

Quantitative Metrics

Focused Performance

- Ground Clearance, measured to the lowest non-wheel and non-legged chassis portion.
- CG height from the ground plane.
- Turning radius. Measurement of chassis turning radius on flat, hard surfaces. By definition, zero for all holonomic mechanisms with 3 or more control DOF.
- Maximum static slope. Measurement of chassis static slope regime along both lateral and longitudinal axes.
- Maximum dynamic slope. Measurement of chassis dynamic slope regime along lateral and longitudinal axes during peak actuation of control DOF.
- Maximum isolated obstacle height traversed.
- Maximum isolated ledge down height descended.
- Maximum isolated crevasse than the mechanism can span.

Broad Environmental

- Flat obstacle field traversal performance, measured in average traversal speed, cumulative odometry accuracy, and average power consumption per foot.
    - Field with mean obstacle size of 6 inches, variance 3 inches, average density of 25% (i.e. 75% freespace along the 2D floor plane).
    - Field with obstacle size 12 inches, variance 6 inches, average density 25%.
    - Field with obstacle size 36 inches, variance 18 inches, average density 50%
- Sloped plane climbing, measured in average traversal speed upslope, odometry accuracy, and average power consumption per foot.

    - 10% grade with mean obstacle size of 6 inches, variance 3 inches, average density of 25% (i.e. 75% freespace along the 2D floor plane).
    - 20% grade with mean obstacle size of 6 inches, variance 3 inches, average density of 25% (i.e. 75% freespace along the 2D floor plane).
    - 40% grade with mean obstacle size of 6 inches, variance 3 inches, average density of 25% (i.e. 75% freespace along the 2D floor plane).
- Sloped plane descent, measured in average traversal speed downslope, odometry accuracy, and average power consumption per foot.
    - 10% grade with mean obstacle size of 6 inches, variance 3 inches, average density of 25% (i.e. 75% freespace along the 2D floor plane).
    - 20% grade with mean obstacle size of 6 inches, variance 3 inches, average density of 25% (i.e. 75% freespace along the 2D floor plane).
    - 40% grade with mean obstacle size of 6 inches, variance 3 inches, average density of 25% (i.e. 75% freespace along the 2D floor plane).

Instrument Deployment and Sample Manipulation

Instrument deployment consists of placing a specified scientific instrument so it is pointing at, near to, or in contact with a specified sample. It includes moving or actuating the instrument while it is in contact. The deployed instrument may be a small measuring device, a large subsurface drill or a set of instruments (e.g., seismometers) that need to be placed in a particular pattern.

Sample manipulation involves picking up an un-modeled sample, orienting it in a specified fashion and placing it in a different location. It also includes preparation of samples such as breaking, scraping, cleaning, brushing, etc.

The above are both required for taking measurements from a sample using multiple instruments not all necessarily mounted on the arm at the same time, including the acquisition of a sample from the environment and transfer to rover interior instruments.

An instrument deployment or sample manipulation operation may consist of the following sub-tasks:

1. *Target detection* – target rock or other scientific sample is detected (see section on Science Planning and Perception), relative position and appearance noted.
2. *Approach* – robot maneuvers to bring target within range of sensor or workspace of manipulator. This requires the robot to somehow keep track of where the target is in relation to itself.
3. *Placement* – sensor or tool placed at appropriate location and relative orientation on or inside target. This does not apply to remote sensors that need only be pointed at a target.
4. *Measurement or manipulation operation* - scientific data acquired from a target using correctly positioned instruments, or target manipulated or otherwise operated upon by correctly positioned effectors.

Functionality Metrics

Qualitative functionality metrics.

- **Approach and instrument or tool placement** – Difficulty level of rover approach to a target and subsequent instrument or tool placement, with the different *levels of autonomy* and *robustness*:

1. Simple remote sensing; point instrument at target from a distance, do not maneuver robot. Target is large enough to fill instrument FOV.
2. Remote sensing with vehicle maneuver so as to get better view of target (e.g. to ensure target fills sensor FOV or optimal viewing geometry).
3. Simple surface contact measurement. Robot approaches target and places single instrument against target surface with centimeter precision and arbitrary orientation with respect to sample surface. E.g. Sojourner APX or Nomad spectrometer.
4. Complex surface contact measurement. Robot approaches target and places one or more instruments against sample surface with millimeter precision, control of instrument orientation against surface, and/or force control.
5. Microscopic and intra-cavity measurements.

		Approach and Placement Robustness			
		Fragile	Intermediate-Fragile	Intermediate-Robust	Robust
Level of Autonomy	Direct Tele-operation				
	Supervized Tele-operation				
	Highly Autonomous				

Where

- **Level of autonomy**
    1. **Direct tele-operation**, operators in high-bandwidth, low latency contact (astronauts at worksite or nearby).
    2. **Supervised tele-operation**. Several communications cycles routinely required for maneuvering the rover to bring the target within range of the sensing or manipulation apparatus and the following sensing or sample handling operation.
    3. **Highly autonomous**. Operators designate samples and intended measurements. Robot autonomously maneuvers to bring samples within range and manipulates or obtains sensor measurements from them. Robot only infrequently needs to contact human operators to deal with problem situations, and multiple samples are routinely examined between each communications cycle.

- **Approach and placement robustness:** complexity of target and environment that robot can routinely handle without failing or requiring additional operator interventions during target detection, approach and placement phases.
    1. **Fragile.** Failures due to:
        - Lighting variations
        - Shadows
        - Interaction with obstacle avoidance system
        - Non-continuous view of target due to robot motion
        - Changes in target appearance due to robot motion
        - False targets in proximity to real target
        - Occlusion of target
    2. **Intermediate Fragile.** Robust to:
        - Lighting variations
        - Shadows
        - Mild changes (scaling) in target appearance due to robot motion
    3. **Intermediate Robust**. Robust above plus:
        - Interactions obstacle avoidance system.
        - Changes in target appearance due to robot motion
        - Non-continuous view of target due to robot motion
    4. **Robust.** Robust to above plus:
        - False targets in proximity to real target
        - Occlusion of target
        - False targets in proximity to target.

6. **Sample preparation**
    1. Mechanically Clean sample surface (< mm abrasion)
    2. Chemical preparation
    3. Core sample to 1 cm depth.
    4. Access interior of sample
    5. Advanced sample preparation (thin sections, *et cetera*).

		Autonomy Robustness			
		Fragile	Semi-Fragile	Semi-Robust	Robust
Level of Autonomy	Direct Tele-operation				
	Supervized Tele-operation				
	Highly Autonomous				

- **Sample manipulations** (does not include placing instruments) -

- Nudge sample – YES/.NO:

		Manipulation Robustness			
		Fragile	Semi-Fragile	Semi-Robust	Robust
Level of Autonomy	Direct Tele-operation				
	Supervized Tele-operation				
	Highly Autonomous				

Where

- **Manipulation robustness:** complexity of target and environment that robot can routinely handle without failing or requiring additional operator interventions during target manipulation operations, subsequent to target detection, approach and tool placement phases.

1. **Fragile.** Failures due to:
    - Lighting variations
    - Shadows
    - Irregular targets
    - 2x target size variations
    - 2x target mass variations
    - Partially buried targets
    - Fragile targets
2. **Intermediate Fragile.** Robust to:
    - Lighting variations
    - Shadows
    - 2x target size variations
    - 2x target mass variations
3. **Intermediate Robust**. Robust above plus:
    - 10x target size variations
    - 10x target mass variations
4. **Robust.** Robust to above plus:
    - Irregular targets
    - Partially buried targets (where appropriate)
    - Fragile targets

- Flip over sample – YES/.NO:

		Manipulation Robustness			
		Fragile	Semi-Fragile	Semi-Robust	Robust
Level of Auton	Direct Tele-operation				

	Supervized Tele-operation				
	Highly Autonomous				

- Pick up sample– YES/.NO:

		Manipulation Robustness			
		Fragile	Semi-Fragile	Semi-Robust	Robust
Level of Autonomy	Direct Tele-operation				
	Supervized Tele-operation				
	Highly Autonomous				

- Orient sample for arbitrary viewing geometry– YES/.NO:

		Manipulation Robustness			
		Fragile	Semi-Fragile	Semi-Robust	Robust
Level of Autonomy	Direct Tele-operation				
	Supervized Tele-operation				
	Highly Autonomous				

- Blast sample into smaller pieces– YES/.NO:

		Manipulation Robustness			
		Fragile	Semi-Fragile	Semi-Robust	Robust
Level of Autonomy	Direct Tele-operation				
	Supervized Tele-operation				
	Highly Autonomous				

- Break **selected** piece off large sample (not drilling) – YES/.NO:

		Manipulation Robustness			
		Fragile	Semi-Fragile	Semi-Robust	Robust
Level of Autonomy	Direct Tele-operation				
	Supervized Tele-operation				

	Highly Autonomous				

- Sample transfer
    - To self for transport
    - To self for analysis
    - To sample isolation container
    - To other robots

The autonomous manipulation system includes several technologies. Under each technology, we have identified key sub-functionalities. We will give a single qualitative score for each technology based on the extent to which the sub-functionalities are present

Robotics Metrics

- Navigation
    - Target Tracking
        1. No target tracking – move blindly to a target select from meters away using position estimation [SCORE 0]
        2. Track target while maintaining view of the target throughout the traverse [SCORE 1]
        3. Track target with obstacle avoidance enabled. Require the tracker to reacquire target after skirting off to avoid an obstacle [SCORE 2]
    - Obstacle Avoidance
        1. No obstacle avoidance during a manipulation maneuver [SCORE 2]
        2. Full obstacle avoidance on board during a manipulation maneuver.

- Vision-Based Manipulation
    1. Look and Acquire – rover acquires an image, generates a terrain map, identifies target location, drives and acquire target using rover position estimation [SCORE 1]
    2. Continously Look then Acquire – rover acquire an image, a target is selected, rover continuously tracks target while driving towards the target. Once in vicinity of target, rover acquires target [SCORE 2]
    3. Continously Look and Visually Acquire – same as above, but acquire target by dynamically identifying the manipulator location and the target location from visually information rather than relying on know manipulation kinematic location [SCORE 3]

- Intelligent Sensor-Based Manipulation
    - Use active vision, were the camera position and orientation and autonomously controlled in conjuction with the manipulation operation.

Operating at dawn, morning night

Sample (cross) contamination

- Cleaning of mechanisms
- Lubricants
- Outgassing?
- Cleaning optics/field re-calibration/compensation

- Visual servoing for instrument deployment should go here (mobility autonomy).

Drilling:

- Lubricants
- Coring?
- Sample return
- Contamination?
- Material:
  - Sand
  - Rock
  - Cryogenic ice
  - Coping with unforeseen changes
- Sensing/telemetry
  - In-situ
- Autonomy

Quantitative functionality metrics

These metrics will have numeric values in the context of concrete scenarios

General:

- Robot run-time to place instrument from initial target designation to final placement. (excludes operator latency)

- **Max Distance from Targets**: Maximum distance at which target can be designated for manipulation operation. This is dependent on many rover parameters including camera optics.

- **Number of successful sample manipulation or contact sensing operations per communications cycle.** For direct hi-bandwidth, low latency tele-operation this number is zero. It is a fraction if multiple communications cycles are needed.

- Precision of Engagement – the final precision of the acquistion or placement operation position and orientation per distance traveled.

- Robustness – Statistically estimated based on experimental data that the manipulation operation will success given a set of initial conditions (distance from target, terrain difficult, rover parameters, etc.)

- Max Secondary Target Dispersions – that can be measured through a combination of max radius and angle of the secondary target relative to the primary target. The larger the second target dispersions are, the more difficult is the autonomous manipulation maneuvers.

- Target Loss Duration in Cycles – the number of cycles that the closed loop system can handle without seeing the target. The number of cycles is used here instead of time or distance because these quantities are not invariant.

- Processing Power – the number of processing cycles required for the operation of the algorithms including the driving and manipulation portions

Other Required Resources – the resources that are required by the systems other than processing cycles such as percentage of camera usage, power, I/O lines, etc, continuous mast operations, etc. (these are system dependent).

Drilling (Mars relevant!)

- Drilling depth, diameter
- Drilling power consumption
- Speed

Science Perception, Planning and Execution

Science perception consists of locating scientifically interesting targets and making scientifically relevant observations of the environment. Science planning creates a plan whose elements are science tasks to be performed, and constraints on those tasks, taking into account the robot's resources (power, instruments, time, etc.), and the value of different kinds of future science observations, given the current state of knowledge. Science planning may be completely autonomous or done in collaboration with scientists. Science execution consists of using the robot and its instruments to perform the science tasks and collect relevant science data. Science execution monitors the state of the robot and its environment, reacting to changes either with actions in the existing plan, or by requesting a new or modified plan. Planning and execution includes the architecture for interactions between planners, the executive, and other system components. It includes the method for extending the planning horizon, and for generating or modifying plans in response to new information.

Qualitative Metrics

Ground science planning tools: *Scientist run mission*

5. Large rover staff. Scientists specify instrument and target tasks. Rover operations personnel generate detailed sequence to accomplish tasks, possibly rejecting some tasks that don't fit resource & operational constraints.
6. No major changes to science plan by rover ops. Rover ops personnel add engineering details and housekeeping tasks to plan.
7. Scientist-generated plan is nearly complete. Rover ops personnel add navigation and arm placement trajectories.
8. All planning and sequencing is accomplished by scientists.

Ground science understanding: *Virtual presence on planet surface.*

1. Raw data returned. Individual images available.
2. Derived 2-D data products (e.g., panoramas).
3. High-fidelity terrain model with ability to interrogate and annotate terrain features.
4. High-fidelity virtual presence in remote environment.

On-board planning and execution: *Commanding level and responsiveness.*

5. Plan is a detailed, time-stamped sequence of low-level commands. Behavior entirely defined by input; system's default response to problems is to halt.
6. Plan allows flexible time specification and contingencies, enabling a family of behaviors.
7. Planner allows a prioritized list of tasks (instrument and target tasks), with constraints among them.
8. Very high-level science goal commanding (e.g., characterize site, find life). System responds to science opportunities and recovers from most faults. System adapts to rover degradation.

On-board science perception: *Site exploration and characterization.*

0. [Scientist selects targets. Data acquisition performed without interpretation.]
1. Scientist selects targets. System selectively returns data based on pre-defined filters.
2. System selects targets based on scientist-specified tests.
3. System characterizes site. E.g. recognizing groups of similar objects and finding representative samples, determining gross site properties such as rock size and shape distributions.
4. System recognizes unforeseen opportunities to collect data confirming or denying existing scientific hypotheses about the site.

Feature a: Onboard data reduction to eliminate redundant or irrelevant measurements. E.g. generating image panoramas, 3D models in lieu of multiple images.

Site complexity

1. Antarctic ice sheet complexity: Candidate science targets sparsely distributed (one per image), easily distinguished from a uniform background (e.g. meteorites on Antarctic ice sheet).
2. Desert complexity: Moderate target density, background maybe similar to targets (e.g. rocks on sandy desert), slight variations in background.
3. Moraine complexity: Extreme clutter, potential science targets everywhere, occluding each other.
4. Stream bed complexity: Diversity of target types and sizes.

Feature a: Unstable environment, noticeable changes occur during course of investigation, possibly because of rover actions.

Feature b: Unknown environment, no prior knowledge to guide investigation (e.g. no prior visits or orbital images).

Science return

1. Mild. Better estimates of well known scientific parameters describing site.
2. Significant. Returned data enables distinction between competing hypotheses.
3. Revolutionary. Totally unexpected discoveries.

Quantitative Metrics

Mission size:

- Number of targets investigated over mission
- Area explored
- Number of sensors

Efficiency:

- Number of command cycles necessary to perform tasks
- Number of science targets investigated / command cycle
- Command cycles / data volume
- Science quality (?) / data volume
- Science quality (?) / command cycles

Planning:

- Planning horizon (time or steps).
- Relative duration of science planning with and without systems

Perception:

- Classification false positives, false negatives

Robot-Robot Interaction

Robot-robot interaction consists of two or more robots working together to accomplish a shared task. This includes planning and executing distributed inspection or assembly tasks. It also includes coordination of motion and information sharing to product joint views of the same object from multiple sensing robots, coordinated action of multiple manipulators (may be needed for a massive or non-rigid object, or to hand off objects between robots), and tasks enabled by coordinated sensing and manipulation by a robot team (for instance, when a separate sensor is needed to improve a manipulator's information about the far end of a beam that it is mating). Robot-robot interaction covers the architecture of interactions, including allocating sub-goals to robots, planning sub-goals, synchronizing execution between robots, and reacting to new information as a group during task execution.

Qualitative Metrics

- Distributed exploration
    1. Verify and estimate performance for operator-specified multi-robot coverage patterns.
    2. Execute coverage patterns with synchronization between robots as necessary to enforce resource constraints, like avoiding collisions (note that different robots may need to inspect the same area, either because they have different sensors, or because they need periodic cross-calibration).
    3. Plan individual coverage patterns and execute cooperatively, given operator-specified sub-areas.
    4. Allocate sub-areas to robots.
    5. Replan coverage dynamically, for example in response to robot failure or opportunistic discovery of a science target.
- Distributed assembly
    1. Verify and estimate performance for operator-specified assembly plans.
    2. Execute assembly plans with synchronization between robots as necessary to enforce resource constraints.
    3. Plan individual sub-tasks and execute cooperatively, given operator-specified sub-goals.
    4. Plan individual sub-tasks based on robot-specific skills (heterogeneous robot teams)
    5. Allocate sub-goals to robots.
    6. Replan assembly dynamically, for example in response to robot failure or unanticipated

- Coordination architecture
    1. distributed
    2. master/slave / centralized
    3. moving master (Mataric)
    4. anarchy
- Coordinated sensing by robot teams
    1. Execute coverage patterns which simultaneously provide multiple views of the same object.
    2. Precisely localize robots with respect to each other.
    3. Optimize geometric configuration for quality of information, while avoiding occlusions and collisions.
    4. Join precise formations and possibly maintain their shape in motion (for example, in support of synthetic aperture stereo vision).
- Coordinated manipulation by robot teams
    1. Hand off objects from one manipulator to another.
    2. Use multiple manipulators to move different parts of a flexible or non-rigid element (e.g., anchoring two ends of a cable).
    3. Use multiple manipulators to move a stiff object (tighter control constraints, may need force sensing).
    4. Optimize geometric configuration for manipulator dexterity, avoiding collisions.
    5. Dynamically change grip during the task to improve dexterity.
- Coordinated sensing and manipulation by robot teams

    1. Manipulator robots perform simple tasks using geometric control updates from sensing robots.
    2. Optimize geometric configuration for both types.
    3. Dynamically reconfigure both types for best performance.
    4. Graceful team performance degradation during individual robot failure
- Logical level of interaction (semantic, etc...)
- Scalability

Quantitative Metrics

- Number of robots. For fielded systems, just report how many robots were used in parallel. For current state of the art, this reports the number of robots we can successfully control before the system starts to break down. "Starts to break down" should be formally defined, if possible (perhaps when the parallel efficiency drops below a certain level?). It may be that, for our scenario, the limit on the number of robots we can control is way beyond the size of any group we could conceive of launching, in which case this metric isn't as interesting (but we should still at least report that fact). **I think we want to distinguish maybe with separate metrics, Theoretical maximum robot team size (for a given architecture) versus maximum demonstrated robot team size (much smaller for everyone I know!) –Illah**
- Mean time between robot-robot interaction failures – remove or change to graceful degradation
    - Measure both damaging failures (e.g., collision and lose a robot, component floats away) and need for operator interventions
- Parallel efficiency. This is a number 0-1. If 3 robots can do the job at 2 times the speed of a single robot, the parallel efficiency of the 3 robot group is 2/3. We define this number by picking a group size (based on the scenario) and then reporting the corresponding efficiency. This will depend strongly on the parameters of the scenario, as well as on the cooperation capabilities. **This measure of superlinearity can be done either looking at time to completion or energy consumed total. Although your formulation is one way of doing it mathematically, we should ask a researcher in the area to see what's commonly done. –Illah The terms frequently used in the parallel computation community are speedup and efficiency. Speedup is $S(N) = T(1)/T(N)$ where $T(k)$ is the time required to perform the task with k processors. Efficiency is $E(N) = S(N)/N$, matching the "definition" above. -Trey**
- Hierarchic and Simple Social Entropy

Tucker's Social Entropy measure is an interesting way of characterizing a robot team, but I wouldn't say a team is better if it has a higher or lower entropy.

- Precision of robot-robot localization and accuracy of formation shape
- Various accuracy and speed metrics from the mobility and manipulation functionalities, but measured for systems that use distributed sensing and/or manipulation.
- # of Coordinated degrees of freedom maybe?

Human-Robot Interaction

Human-robot interaction consists of a continuum ranging from human responsibility for each movement of the robot using human sensing (sometimes called teleoperation or telepresence) to high-level commanding and supervising of the robot's goals using natural interfaces such as language. Human/robot interaction also consists of the sensing algorithms required to locate and track humans and their body parts and the reasoning algorithms required to interpret human intentions and actions.

Qualitative Metrics

Distance interfaces

- Teleoperation
    1. Joystick and computer screen
    2. Video overlays and some non-video sensor display (e.g., forces)
    3. Reconstructions and enhanced sensory information
    4. Simulations and predictive displays
- Communication from robot
    1. Raw telemetry
    2. “Filtered” telemetry
    3. Internal state information
    4. Explanation of activities

Task-level interaction

- Mixed-initiative planning
    1. Multi-agent planning that includes humans as an agent
    2. Collaborative planning between human and robot
    3. Collaborative, real-time re-planning
    4. Plan recognition of human agents
- Adjustable autonomy
    1. Autonomy either on or off
    2. Operator intervention points fixed before mission
    3. Operator interventions flexible during mission
    4. Operator can intervene at any level at any time and then turn control back to robot

Robot/Human teams in the field

- Human/robot communication
    1. Text-based commands entered using keyboard or mouse
    2. Simple voice commands (e.g., stop, faster, move right, etc.)
    3. Complex voice commands, including referents (e.g., pick up that)
    4. Multi-modal communication (e.g., integration of speech and gestures or speech and graphics tablet)
    5. Dialogue with human about goals and actions
- Sensing of humans
    1. Generic obstacle avoidance and safe movement
    2. Tracking of humans in work environment
    3. Tracking of human body parts (e.g., gestures)
    4. Recognition of humans and their activities
- Gesture recognition
    1. Simple, static gestures
    2. Dynamic gestures
    3. Sign language
- Physical interaction
    1. Holding something (light, tool, cable) for human
    2. Handing objects to human
    3. Taking objects from human
    4. Carrying/rescuing human

Quantitative Metrics

- Bits exchanged to perform task
- Tracking human accuracy
- Tracking human speed
- Ratio of time for crew to do task alone vs. with a robot
- Ratio of time required for crew to tele-operate vs. doing it themselves
- Number of operators per robot (pilots vs. others)