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Forward Acquisition of Soil and Terrain data for Exploration Rover

Improved Traversal for Planetary Rovers through Forward Acquisition of Terrain Trafficability

Planetary Rovers Workshop, ICRA 2013

Yashodhan Nevatia

Space Applications Services

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Deutsches Forschungszentrum für Künstliche Intelligenz GmbH, Robotics Innovation Center · University of Surrey · Astrium, an EADS company · Space Applications Services · Liquifer Systems Group · Astri Polska

Seventh Framework Programme

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Co-authors :

Deutsches Forschungszentrum für Künstliche Intelligenz GmbH – Robotics Innovation Center
Thomas Voegele
Roland Sonsalla

Space Applications Services
Yashodhan Nevatia
Jeremi Gancet
Francois Bulens

University of Surrey
Chakravarthini Saaj
William Lewinger
Marcus Matthews
Francisco Comin
Yang Gao

Liquifer Systems Group
Barbara Imhof
Stephen Ransom
Lutz Richter

Astrium – An EADS Company
Elie Allouis

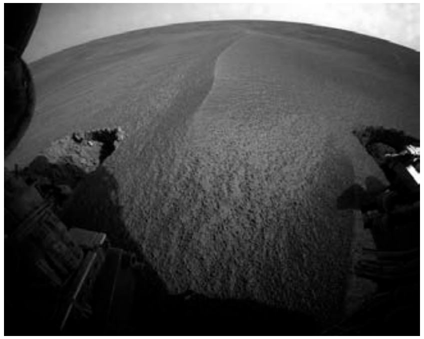
Astri Polska
Krzysztof Skocki

Motivation

- Terrain hazards pose great danger to planetary rovers
  - Difficult to detect visually, even by experts!
  - Sandtraps
  - Subsurface voids
  - Dunes (low traction)
- MER Spirit
  - Immobilized at ‘Troy’
  - No a priori visual indication of hazard
- MER Opportunity
  - Wheels dug in while crossing sand dune
  - Immobilized for 38 sols
- Danger increased with autonomous operations

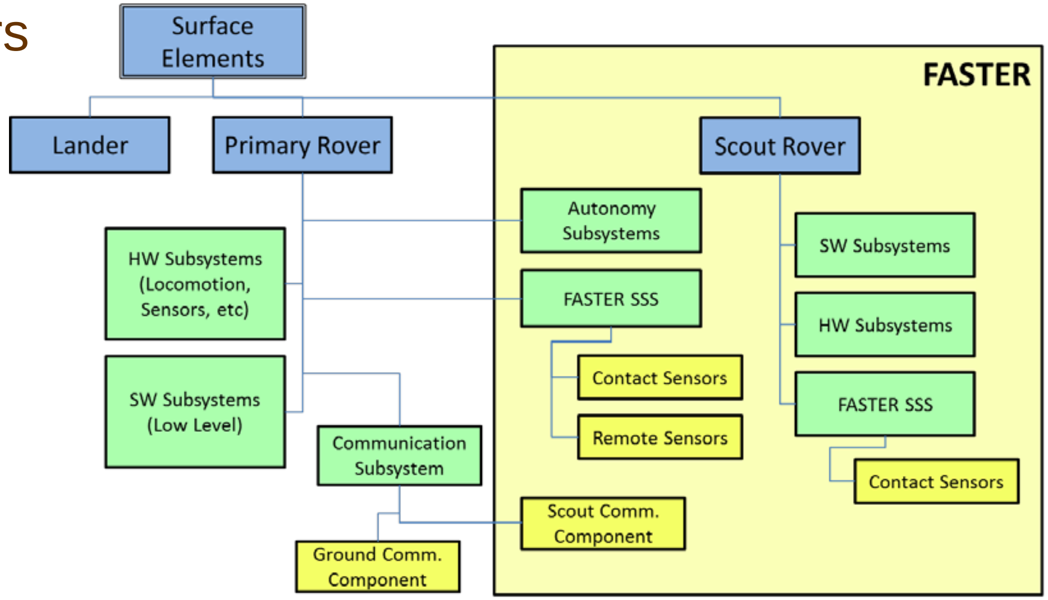
→ Require operation concepts allowing safe & fast traversal!

Photos: NASA/JPL-Caltech



Objectives

- Forward sensing of terrain trafficability
  - Allow detection of hazards with minimal risk to rover
  - Scout rover as forward sensing platform
  - Soil sensors
    - Primary rover sensors
    - Scout rover sensors
    - Remote sensing
  - Cooperative autonomy

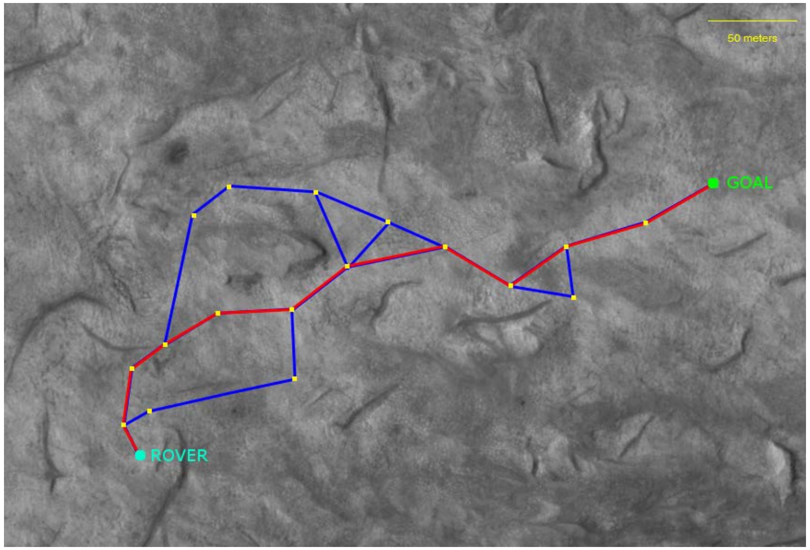


Operations Concept

- Applicable to long traversals
  - Minimal or no science during traverse
- Baseline mission: Mars Sample Fetch Rover
  - Landing site to cache location, return trip
  - Required traversal distance: ~ 15 km
  - Average traversal speed: ~ 170 m per sol
- Ground Planning Phase
  - Identification and specification of traverse command
- On Board Command Procedures
  - Global Path Planning
  - Waypoint Traversal

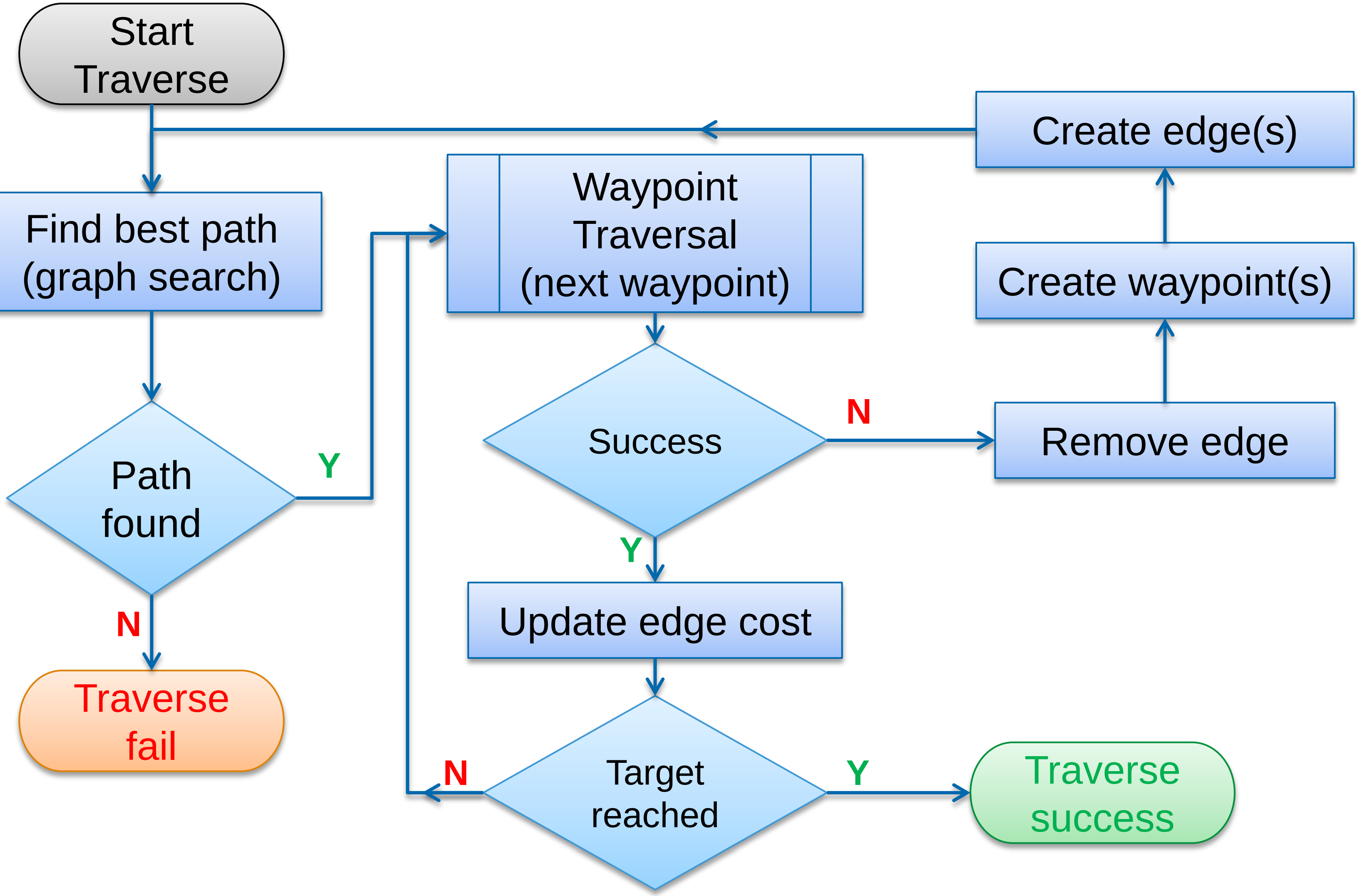
Ground Planning

- Preparation for a single traverse command
- Identification of target location
  - Can be more than one sol away
  - > 200 m

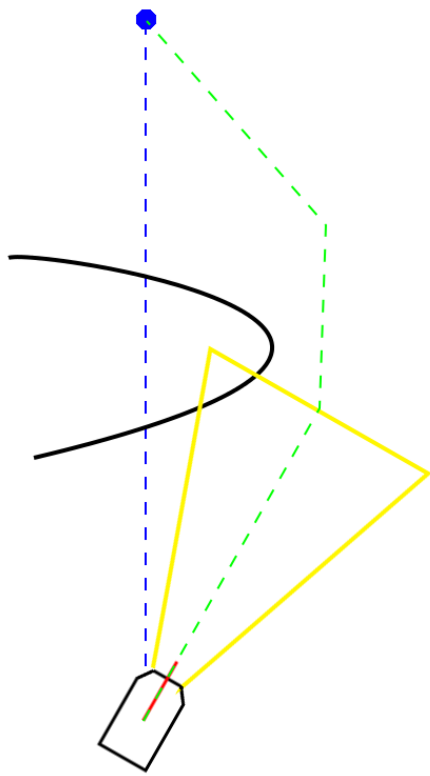


- Identification of potential paths
  - Using orbiter data
  - Path as set of waypoints
    - Straight line between waypoints
    - Estimated (directional) cost of traversal
  - Multiple, interconnected paths
- Paths encoded as a directional graph
  - Waypoints as nodes, costs as edge weights

Global Path Planning



- Similar to behaviours proposed by Volpe et. al. [1]
  - ‘Motion-to-Goal’ and ‘Boundary-Following’



- Rovers turn towards the next waypoint
- Build elevation map
- Artificial target if waypoint is outside map
- Remote soil sensing as input for obstacles
- Path planning
- No path – Obstacle circumnavigation
  - Rovers allowed to rotate slightly

Waypoint Traversal

- Scout begins 'forward sensing'
  - Path updates at scout location as needed (eg. hazard detection)
  - Extension of elevation map on reaching end of path
  - Limited to within line of sight of primary rover

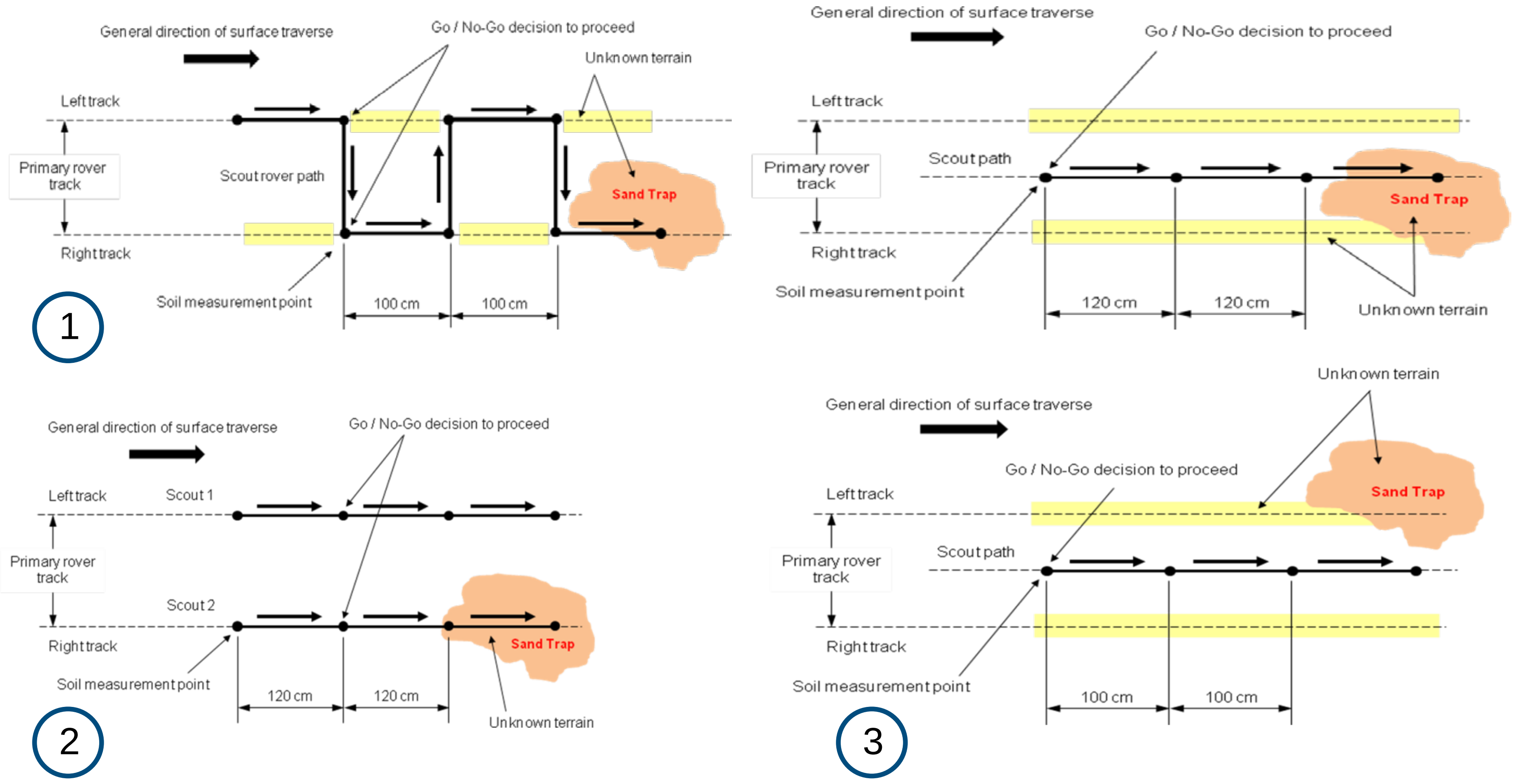
- Primary rover traversal
  - Path update from primary rover location on detection of hazard
  - Scout returns to primary rover location

Waypoint Traversal Failure

- No path found
  - Both rovers together, single new node
- Hazard detection by scout
  - No alternate path
  - Addition of two connected nodes
  - Scout to primary, or vice versa, based on new global path
- Hazard detection by primary rover
  - No alternate path
  - Scout returns to primary rover, single new node

Scout Forward Sensing

- Three scenarios considered with different parameters



Scout Forward Sensing

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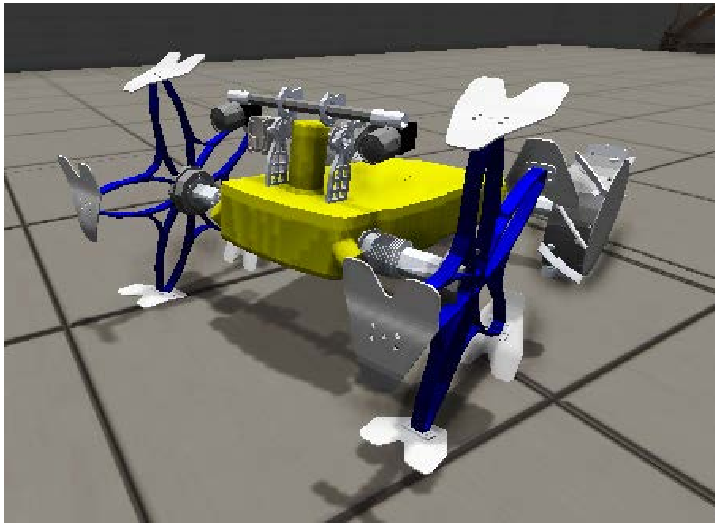
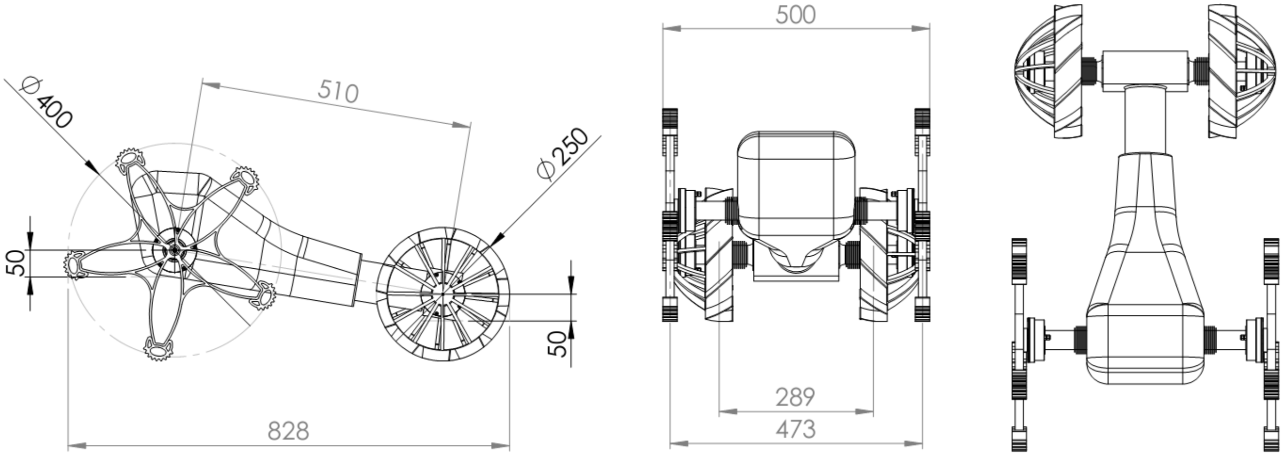
Scenario	Distance between measurement points (cm)	Path(s) taken by Scout(s)	Total measurement time of one cycle (sec)	Longitudinal distance traversed by Scout in 4 h (m)	Actual distance traversed by Scout in 4 h (m)	No. of turns performed by Scout in 4 h	Primary rover max. speed (cm/s)
One Scout							
1	120	Step	160.8	107.5	203.3	215	0.75
	100		157.2	91.6	189.6	~183	0.64
Two Scouts							
2	120	Parallel	81.6	211.8	211.8	0	1.47
	100		78.0	176.5	176.5	0	1.28
One Scout							
3	120	Mean	81.6	211.8	211.8	0	1.47
	100		78.0	176.5	176.5	0	1.28

- Measurement time of 60 s
- Step pattern is too slow to achieve desired daily traverse
- Scenario 3 chosen as baseline
  - Most plausible in terms of mission size and complexity

Scout Rover

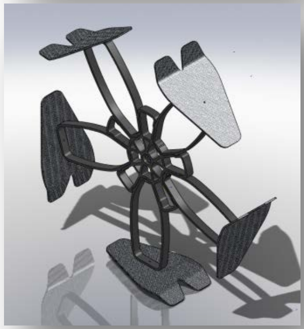
- Small, lightweight platform
  - Fits into typical mission budget
  - ~ 15 kg
- High mobility
- Docking with primary rover for power
  - Full power system too bulky

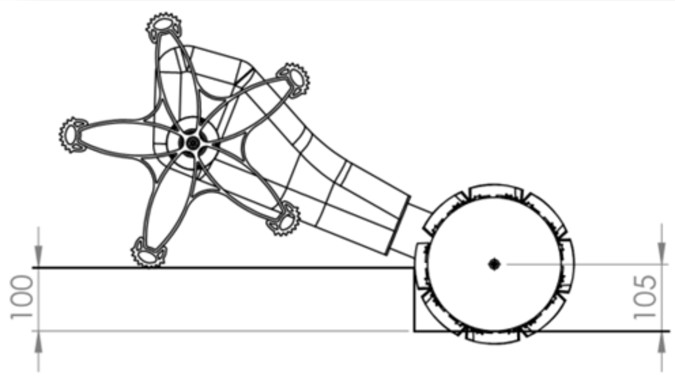


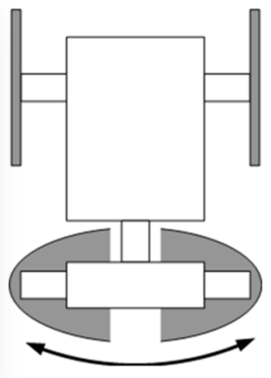


Scout Rover Locomotion

- Wheel Design
  - Front: Legged wheels
  - Rear: Helical wheels
- Steering Concept
  - Skid steering
  - Side-to-side motion
- Chassis
  - DOF along roll axis
- Climbing
  - Front: at least 224 mm
  - Rear: at least 100 mm







Scout Rover Hardware Subsystems

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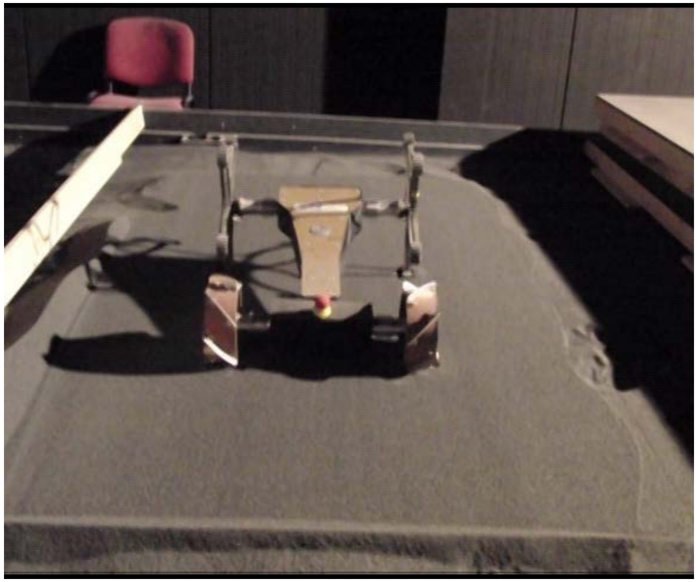
Structure and Mechanisms	
Mass (estimated)	15 kg
Boundary Box	400 x 828 x 500 (H x L x W in [mm])
Locomotion	Front: Hybrid Legged-Wheels (r=200mm) // skid steering Rear: Helical Wheels (r=125mm) // side-to-side steering
On Board Data Handling	
OBC	MIO-5290 embedded single board computer by Advantech
PDH	Each sensor payload will be equipped with its own Microcontroller
Communication	
S-Band Link	802.11g wifi-module at 2.4GHz and 54 Mbps (e.g. Asus WL-330gE LAN to WLAN adapter)
Electrical Power Supply	
Battery	Lithium Polymer @ 22.2V ~8000 mAh
Bus Voltage	Unregulated & 5 V (TBC)
Thermal Control System	
Driving Units	Passive control: radiator and heat transfer paste
Electronic-Satck	Active control: ventilation system
Navigation	
Stereo Camera	Guppy cameras from Allied
Wheel/Body Sensors	6 DoF IMU Body DoF encoder Wheel Turn/Angle Counter Wheel torque mesasurement



Soil Sensing System

- Outputs traversability classification – 'Go'/'No-Go'/'Maybe'

- Remote Sensing
  - Detection of rocks from visual imagery
- Scout Rover Sensors
  - Hierarchical multi sensor suite
  - Camera/IMU, Ground Penetrating Radar
  - Dynamic Plate, Dynamic Cone Penetrometer
- Primary Rover Sensors
  - Wheeled Bevameter
  - PathBeater

Soil Sensing Concepts

Soil Sensor System	Deployment Sequence	Rover in Motion?	Operation Time	Soft Soils	Firm Soils	Rover Load Bearing	Wheel Slip	Duricrusts	Shallow Voids	Moderately Deep Voids	Surface Rocks	Sub-surface Rocks	Soil Strength	Soil Stiffness
Belly Camera / IMU (Leg-Soil Interactions)	S-1, C	Y	C	**X**	**X**	**X**	**X**	*	**X**		**X**		**X**	
Ground Penetrating Radar	S-2	Y	C					**X**	**X**	**X**	**X**	**X**		
Dynamic Plate	S-3	N	<15s	**X**	**X**	**X**		x	x					**X**
Dynamic Cone Penetrometer	S-4	N	≤60s	**X**	**X**	**X**	x	**X**	**X**	**X**	**X**	**X**	**X**	
Wheeled Bevameter	C	Y	C	**X**	**X**	**X**	**X**						**X**	**X**
PathBeater	C	Y	≤20s	**X**	**X**	**X**		**X**	x				**X**	

S-n - Scout Sequence C - Continuous **X** - can be detected x - may be detected □ - cannot be detected * - thin duricrusts only

Remote Sensing

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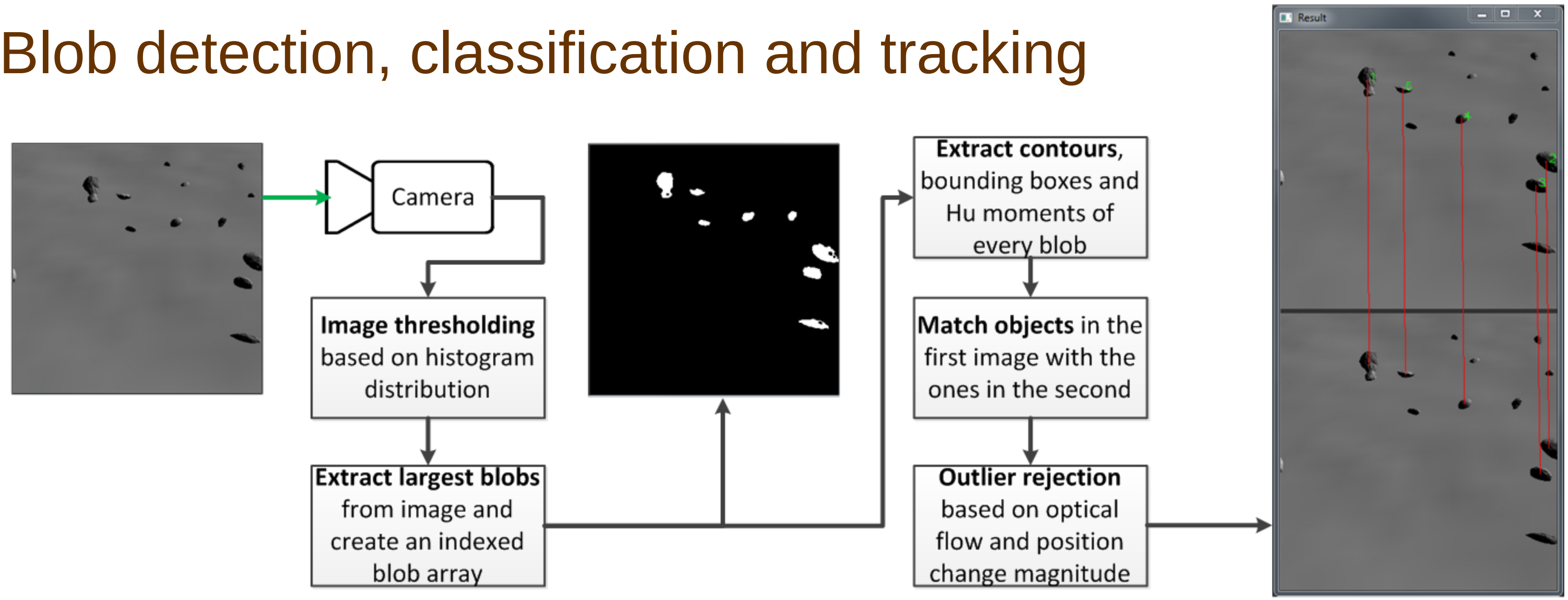
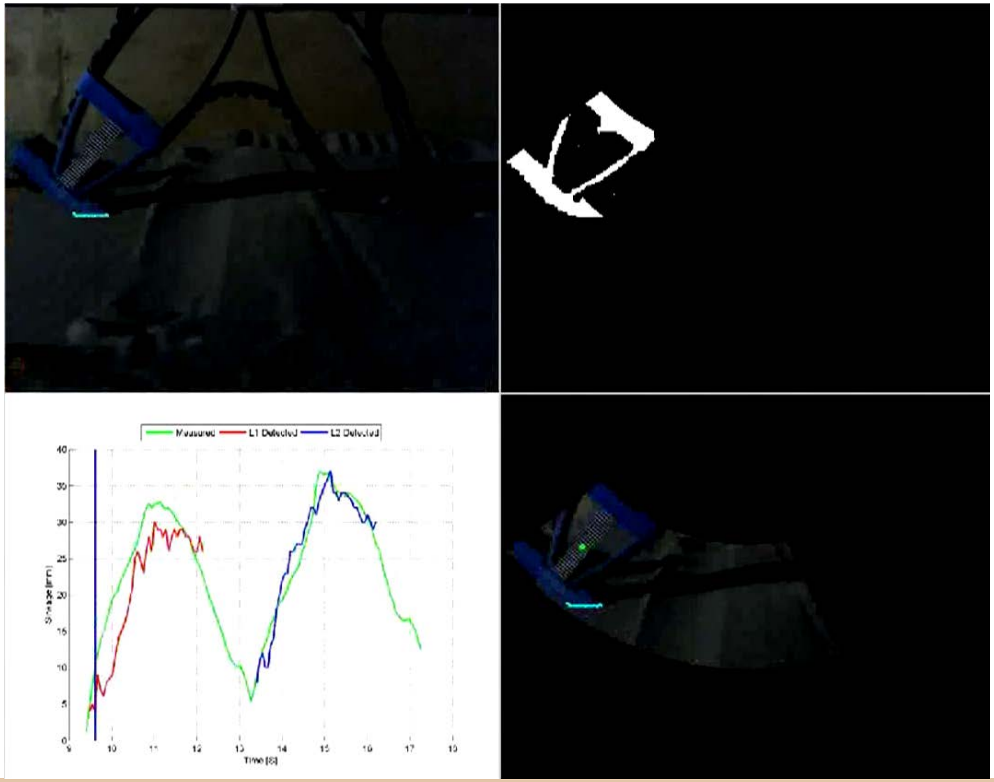
- Semantic feature detection
- Blob detection, classification and tracking



- Also under consideration:
  - Supervised machine learning classifiers
  - Saliency detection, classification and tracking

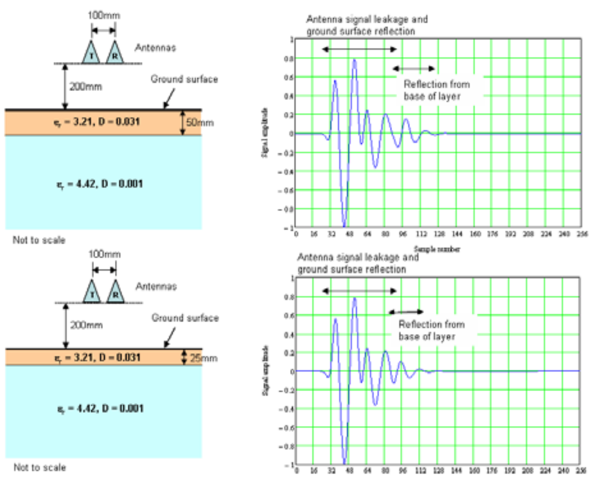
Scout Leg-Soil Interaction

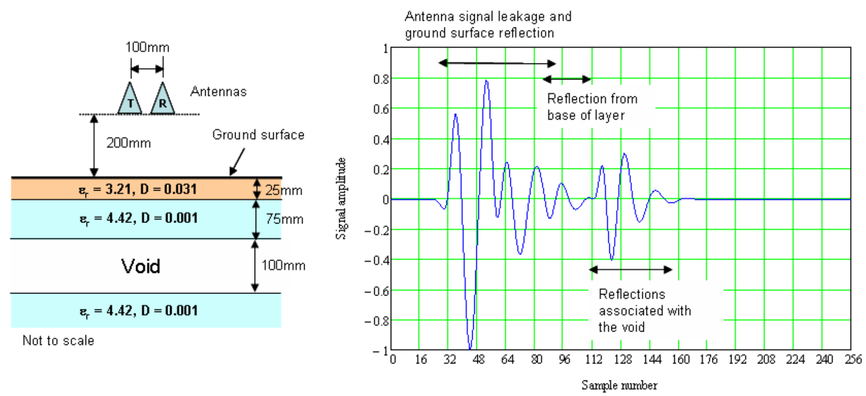
- IMU to measure impact of leg on surface
- Camera placed under chassis to measure leg sinkage
- Specially designed, 3D printed load testing foot



Ground Penetrating Radar

- EM wave reflected at soil boundaries
- Detection of subsurface hazards
  - Voids, rocks, duricrusts
- Scientific data on soil strata
- Preliminary simulations performed by Cobham PLC (UK)





Hybrid DP/DCP Sensor

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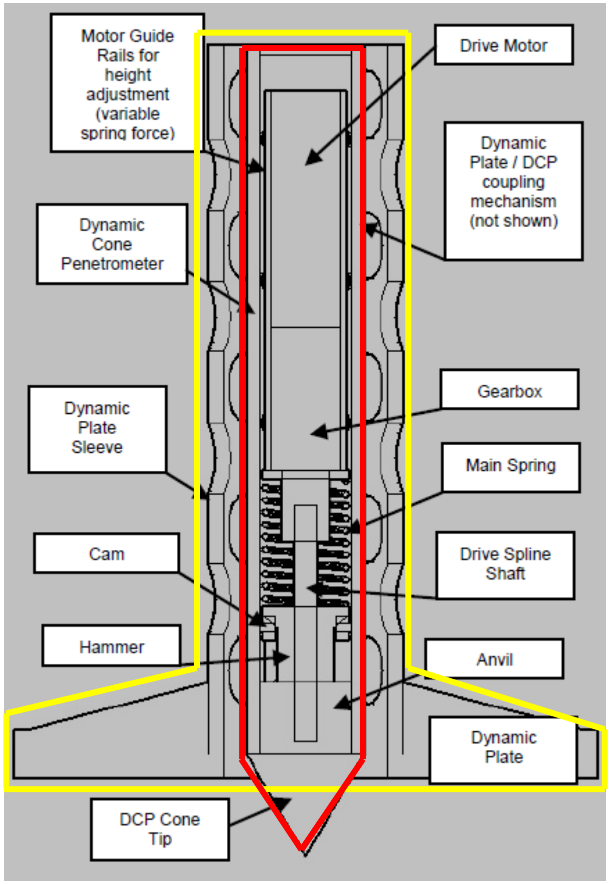
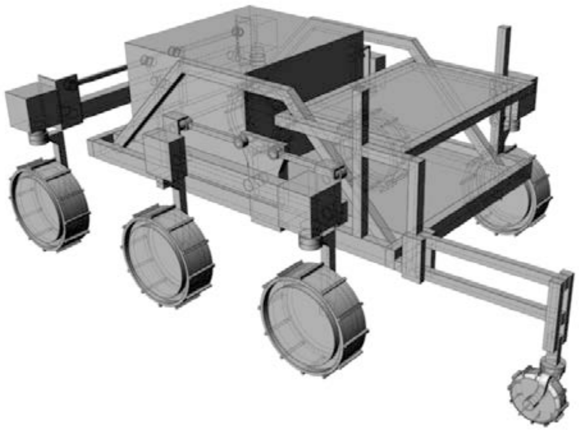
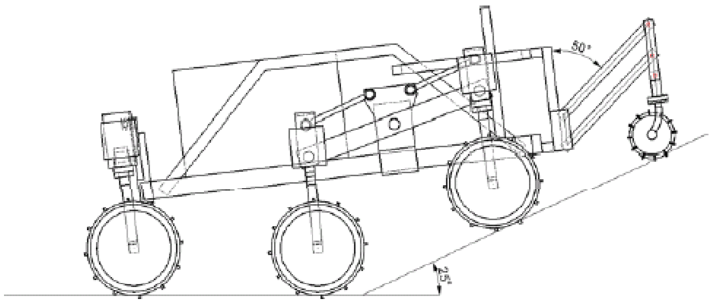
- Combines two contact sensors
  - Use of single electric drive mechanism
  - Plate can be decoupled
- Dynamic Plate
  - Subject terrain to load similar to that applied by the primary rover
- Dynamic Cone Penetrometer
  - Repeated impact of hammer
  - Measures tip penetration & resistance

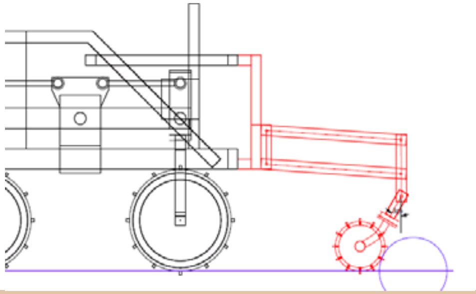


Wheeled Bevameter

- Well known concept for terrestrial use
- Used in MER rovers
  - Offline analysis from rear cam images
- Test wheel mounted in driving direction
  - Representative loading conditions
- Measure
  - Observed wheel rut depth
  - Calculated wheel/vehicle slip
- Estimation of Bekker parameters
  - Usable in mobility models

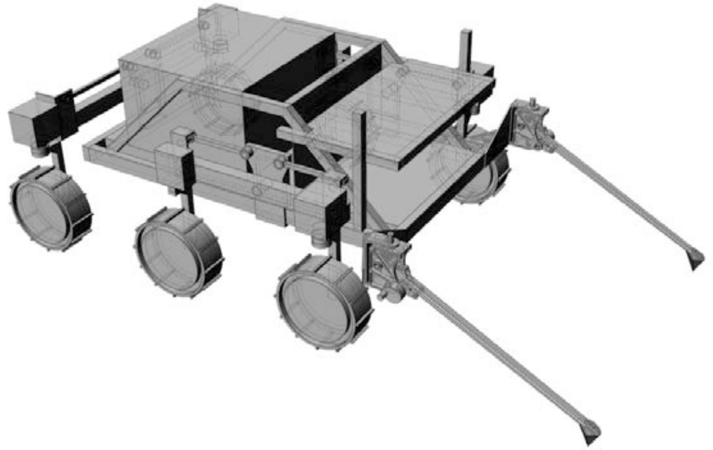


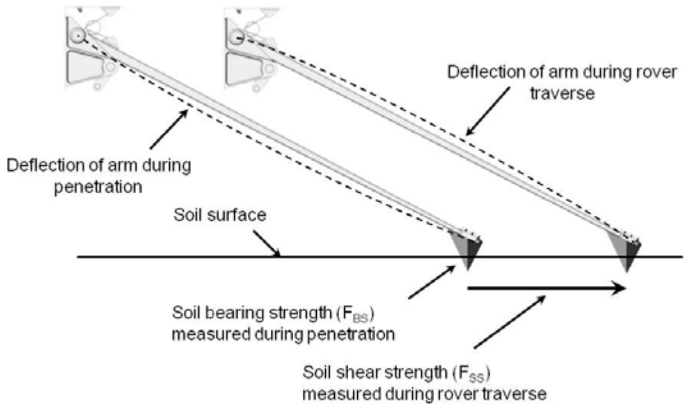




PathBeater

- Novel sensor concept
- Measure the soil characteristics ahead of both front wheels
- Sensor functioning
  - Located above and in front of forward rover wheels
  - Actuated by C-spring, rotating cam driven by electric motor
  - Pyramidal penetrator at end of each arm impacts ground
  - Forward motion while penetrators are in contact with ground





Cooperative Autonomy & Software

- E3 level of autonomy
  - **Adaptive mission operations** on-board
- Partial support for E4 level of autonomy
  - Goal-oriented mission operations on-board
  - Operation concept provides for **goal based traversal**

- Scout Rover
  - Minimal autonomy: path following
  - Emergency autonomy: Return to primary rover

- Primary rover
  - Subsystem architecture based on $G^{en}oM$ with ROS modules

Primary Rover Software Architecture

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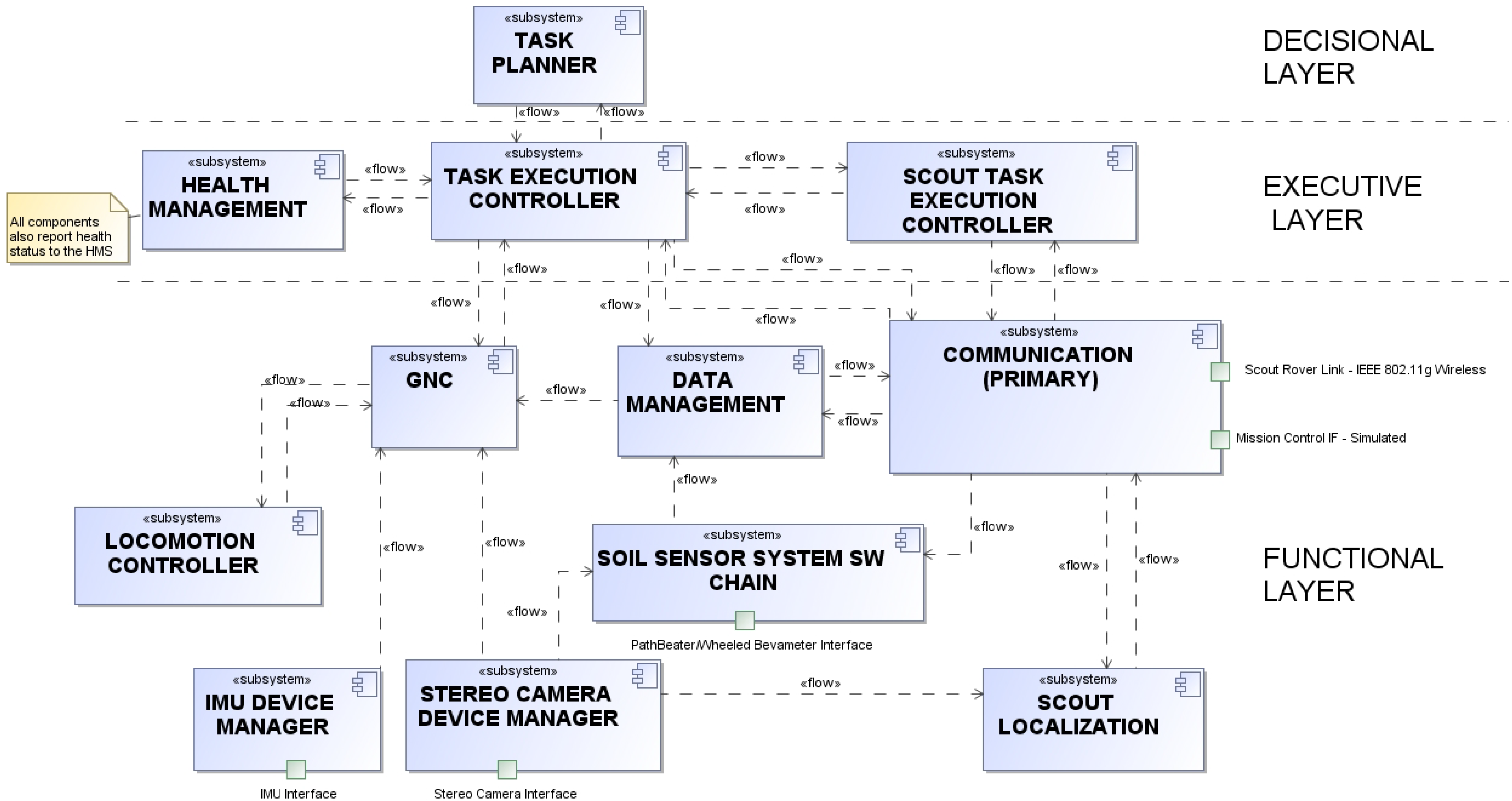

Primary Rover Software Subsystems

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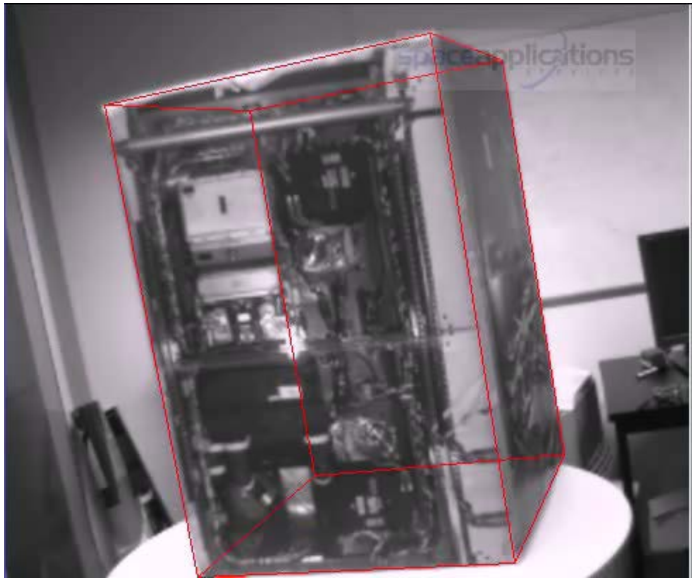
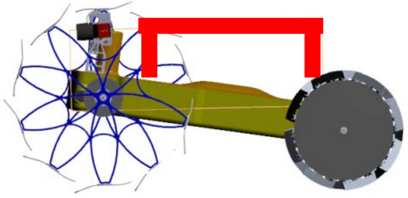
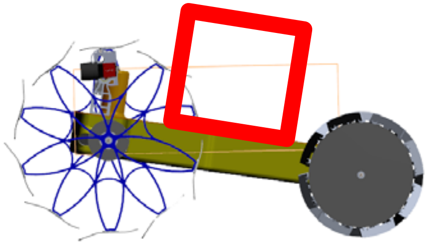
- Task Planner
  - Symbolic planner based on Hierarcichal Task Network [2]
  - Validation of plans based on resources available
- Scout Localization
  - 6DOF tracking of scout in primary rover imagery
  - Two possibilities:
    - SURF point feature based detection
    - Marker based tracking





Single Marker



Multi Marker

Primary Rover Software Subsystems

- Guidance, Navigation & Control
  - Mapping
    - Filtering
    - Combining point clouds from both rovers
    - Iterative Closest Point
  - (Self) Localization
    - Wheel / Inertial Odometry
    - Visual Odometry
    - SLAM using rocks as features
    - Matching of local map with orbiter height maps (prospective)
  - Path Planning
    - D* for path generation over local map
    - Trajectory fitting

System Validation

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- Simulation
  - Validation of cooperative autonomy
  - Gazebo
- Laboratory tests
  - Soil sensor validation with soil simulants
- Field trials (Summer 2014)
  - Use of Bridget locomotion breadboard from Astrium

Photo: PRoVisG Field Trial, 2011

Thank you!

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https://www.faster-fp7-space.eu/

Yashodhan Nevatia

Space Applications Services

yn@spaceapplications.com

Chakravarthini Saaj

Technical Manager

University of Surrey

c.saaj@surrey.ac.uk

Thomas Vögele

Project Coordinator

German Research Center for Artificial Intelligence

thomas.voegele@dfki.de

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[2] R. Kandiyil and Y. Gao, “A Generic Doman Configurable Planner using HTN for Autonomous Multi-Agent Space System,” in *Proc. 11th International Symposium on Artificial Intelligence, Robotics and Automation in Space*, Turin, Italy, 2012.

Traverse Requirements

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- Based on preliminary Sample Fetch Rover planning

Mission Surface Phases	Activities	Duration	Units
Post Landing Checkout			
	Comms establishment & HK status	4	sols
	Initial Post landing checkout	4	sols
	Egress	4	sols
	Post-landing checkout duration	**12**	**sols**
Preparation for Departure from Landing Point			
	SFR commissioning	5	sols
	Landing Site local exploration	2	sols
	Pre-excursion duration (sols)	**7**	**sols**
Sample Cache Acquisition			
	Identification of target location	1	sols
	travel to target location	3	sols
	Verification & confirmation of target	2	sols
	Sample Acquisition	1	sols
	Sample Cache Acquisition Duration	**7**	**sols**
Cache transfer to MSR Lander			
	Identification of target location	1	sols
	travel to target location	2	sols
	cache Transfer	1	sols
	Cache Transfer to MSR Duration	**4**	**sols**
Contingencies			
	Conjunction Allocation (no ops)	**20**	**sols**
	Dust storm or operational contingency	20	sols
	Total Contingency	**40**	**sols**
Total Mission Operations duration		**70**	sols
	Nominal Mission Duration	180	sols
	Duration left for traverse	**110**	**sols**
	Traverse Distance	15	km
	Traverse Margin	1.3	
	Minimum Rover speed	**177**	**m/sol**

MER Spirit

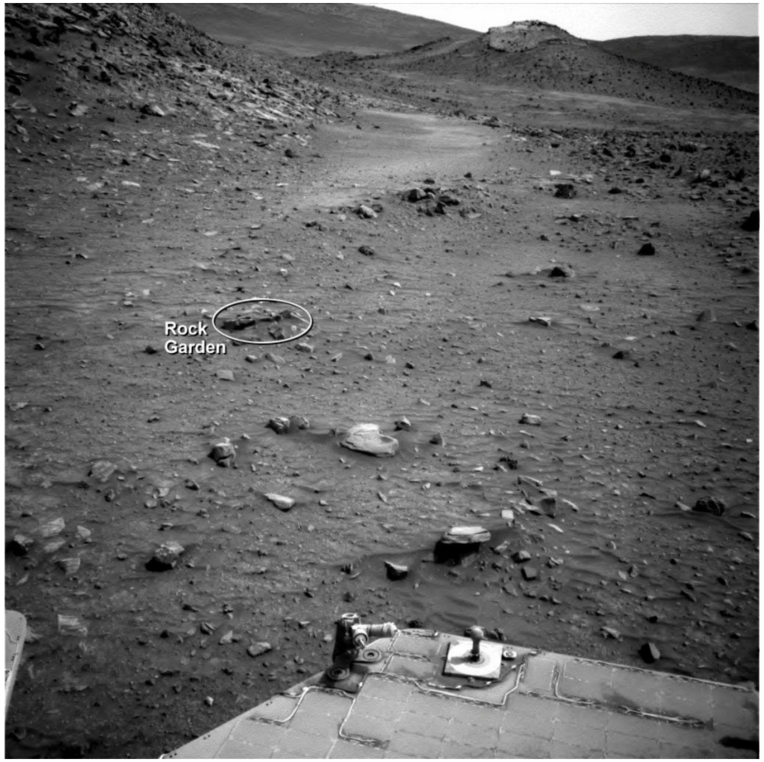
The cluster of rocks labelled “Rock Garden” in this image is where *Spirit* became embedded.

Spirit used its navigation camera to capture this view of the terrain toward the southeast from the location Spirit reached on Sol 1870 (7 April 2009).

The ground just left of the centre of the image is where *Spirit* became embedded on Sol 1899 (6 May 2009). Wheels on the western side of the rover broke through the dark, crusty surface into bright, loose, sandy material that was not visible as the rover approached the site.

Wheel slippage during attempts to extricate *Spirit* partially buried the wheels.

Photo: NASA/JPL-Caltech



MER Opportunity

Opportunity was stuck in a Martian sand dune between Sol 446 (6 April) and Sol 484 (4 June 2005).

The photograph shows the troughs left behind in a soft sand dune where *Opportunity* was stranded for 38 Sols

The problem began on Sol 446 when *Opportunity* inadvertently dug itself into a sand dune. Mission scientists reported that images indicated all four corner wheels were dug in by more than a wheel radius, just as the rover attempted to climb over a dune about 30 cm high.

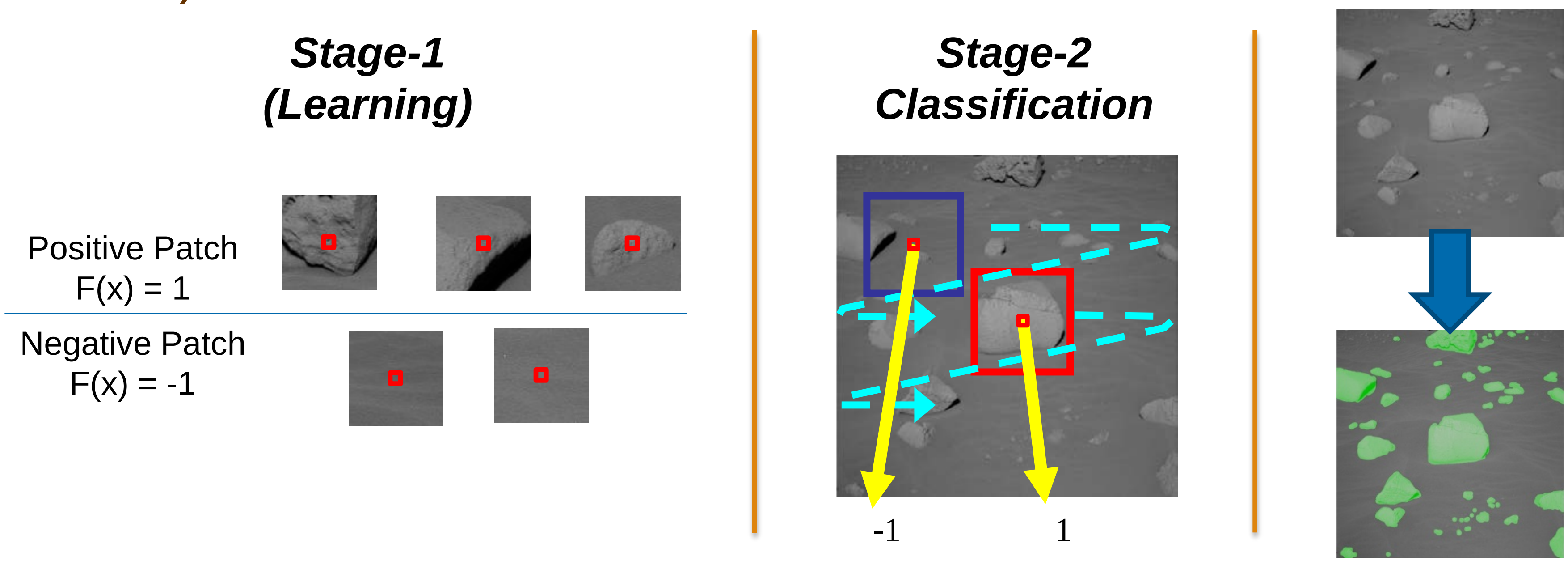
Photo: NASA/JPL-Caltech

Extended Operations

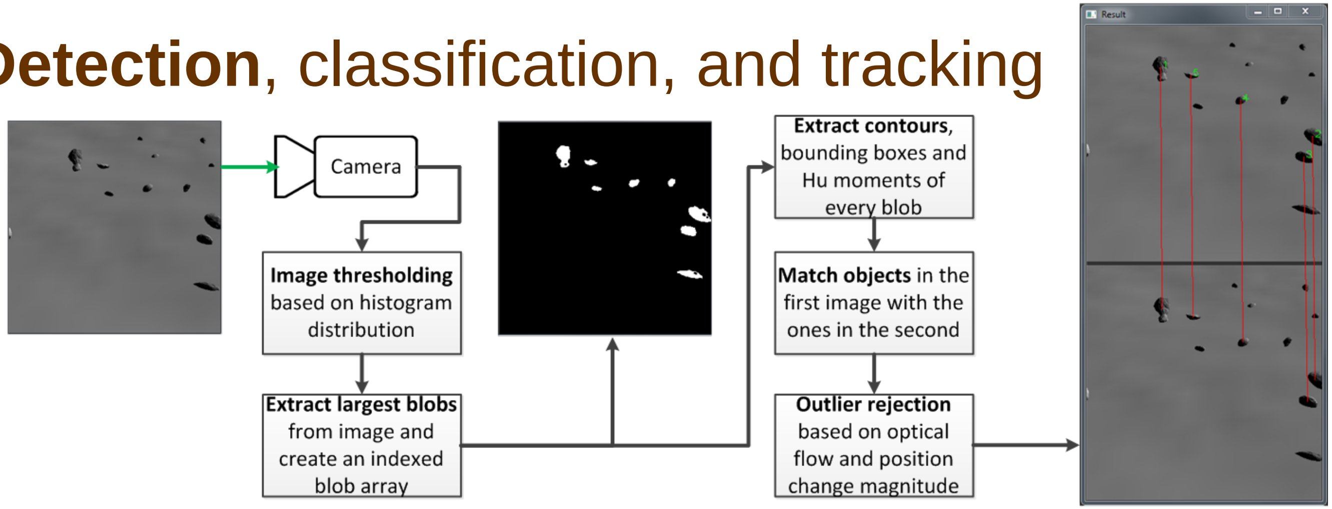
- Exploration or scientific tasks
  - Very useful, but considered out of scope
- Long Term Scouting
  - beyond range of Primary Rover sensors/communication
  - delays in case of wrong trafficability from scout sensors
- Increased requirements for Scout
  - Fully autonomous operation
    - Self localization and task planning
  - Increased power requirements
- Increased mission complexity
  - Relative localization between scout path and primary rover
  - Recharging of scout batteries

Remote Sensing

- Semantic feature detection rather than pixel-based feature detection
- Three approaches are currently being investigated:
  - **Supervised machine learning** classifiers (SVM & Boosted LDA):

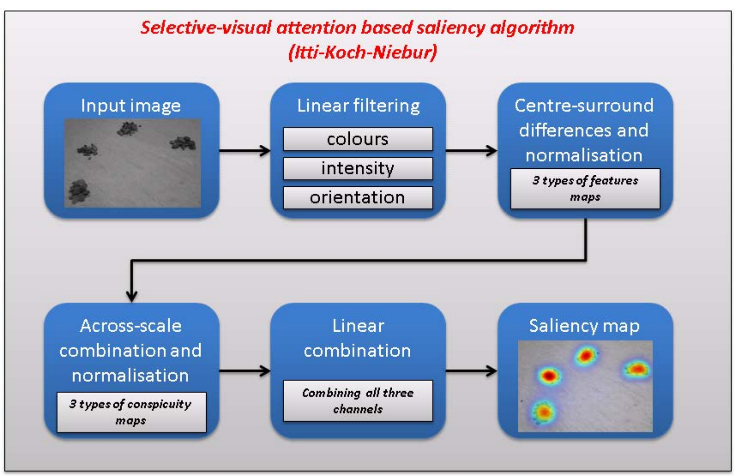


- **Blob Detection**, classification, and tracking



- **Saliency Detection**, classification, and tracking

Stage-1



Stage-2