Improved Traversal for Planetary Rovers through Forward Acquisition of Terrain Trafficability*

Yashodhan H. Nevatia, *Member, IEEE*, Jeremi Gancet, *Member, IEEE*, Francois Bulens, Thomas Voegele, Roland U. Sonsalla, Chakravarthini M. Saaj, *Senior Member, IEEE*, William A. Lewinger, *Member, IEEE*, Marcus Matthews, Francisco J. C. Cabrera, Yang Gao, *Senior Member, IEEE*, Elie Allouis, Barbara Imhof, Stephen Ransom, Lutz Richter and Krzysztof Skocki

Abstract— **Current operations of planetary rovers, especially the planning and execution of traverse operations, rely on human analysis and estimation of non-geometric hazards based on images captured by the rover. Despite the use of advanced path planning algorithms capable of avoiding obstacles, this limits daily traverse distances. This paper presents a system concept for planetary rovers capable of safe traversal beyond the immediate range of navigation through forward sensing of terrain trafficability, resulting in improved traversal speeds.**

I. INTRODUCTION

The past decades have seen a number of robotic missions to the Martian surface. While these missions have been extremely successful in terms of scientific data gathered, as well as technologies and capabilities demonstrated, the rovers have faced significant difficulty traversing the Martian surface. The most notable example of this is the MER Spirit which was immobilized when one of its wheels was trapped in subsurface sand during a commanded drive in April 2009 – no indication of the hazard was visible while the drive was being planned.

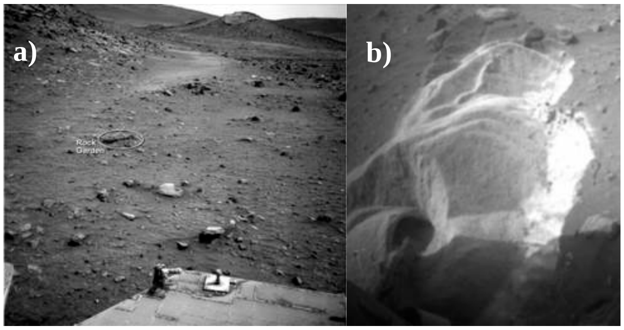


Figure 1. Images from MER Spirit. a) Navigation image showing no indication of hazard, b) Wheel embedded in subsurface sand [Photos: NASA / JPL – Caltech]

To reduce the risk of failure, especially immobilization, current concepts for planetary rover operations rely heavily on human involvement and simulation of rover operations. With regards to traverse operations this includes building up a 3D environment of the current surroundings of the rover based on received imagery, identification of hazards including manual identification of regions with suspected subsurface hazards or high slip, and then planning and validation of paths. While suitable for reducing risk by involving experts for scene and terrain analysis, such operations methodologies limit the distance that can be safely traversed each sol to what is in visible range.

Continued interest in planetary exploration and the success of recent rovers has led to the planning of several future missions to Mars for the next decade. As the expected scientific return from these missions grow, so do the required capabilities and need for autonomous operations that do not require regular human involvement. One such mission, the Mars Sample Return Mission, would require the rover to traverse a large distance from its landing site to a cached sample, and return with the sample to the landing site within a year. Allowing sufficient time for other required operations such as collecting the cached sample and transferring it to the ascent vehicle, as well as contingencies, results in a required daily traversal of approximately 170m – significantly beyond the capabilities of current operations.

This paper presents a system concept enabling planetary rovers to reliably and rapidly traversal of large distances over unknown terrain in preparation for such future missions. The system is based on the forward sampling of soil and terrain characteristics, allowing the autonomous detection of hazards before the rover is at risk. This reduces the need for human intervention and manual analysis of imagery, allowing the traversal to target locations beyond the range of rover sensors.

There are three main components of the proposed system:

1. Scout Rover
2. Soil Sensing System
3. Cooperative Autonomy

The next section describes the operations concept that is proposed for improved traversal, after which each of these three components is expanded. Finally, a brief overview of the proposed approach for system validation is presented.

* Research part of the *Forward Acquisition of Soil and Terrain data for Exploration Rover* (*FASTER)* project, supported by the European Commission through the SPACE theme of the FP7 Programme, under Grant Agreement 284419.

Y. H. Nevatia, J. Gancet, F. Bulens are with Space Applications Services, 1932 Zaventem, Belgium.

T. Voegele, R. U. Sonsalla are with DFKI Robotics Innovation Center, 28359 Bremen, Germany.

C. M. Saaj, W. A. Lewinger, M. Matthews, F. J. C. Cabrera, Y. Gao are with the Surrey Space Centre, University of Surrey, Surrey, GU2 7XH UK.

E. Allouis is with EADS Astrium, Stevenage, SG1 2AS UK.

B. Imhof, S. Ransom, L Richter are with Liquifer Systems group, 1020 Vienna, Austria.

K. Skocki is with Astri Polska, 00-716 Warsaw, Poland.

II. OPERATIONS CONCEPT

While the availability of a free ranging scout rover potentially enables a number of scenarios with greater scientific return, the FASTER operation concept focusses on the ‘traverse phase’ of missions. This phase, the identified long range traversal required in sample fetch missions with minimal science to be performed, is addressed as three components:

- Ground Planning (Traversal Telecommanding)
- Global Path Planning
- Waypoint Traversal

A. Ground planning

This phase comprises the planning efforts prior to sending the traverse telecommand to the primary rover. Operators at Mission Control utilize available terrain data of the Martian surface to determine potential paths to the target location, avoiding large obstacles and geological features that are visible in orbiter data. Building on the representation of a path as an ordered set of waypoints with straight line paths in between, the collated potential paths are represented as a directional graph where each edge represents a path between two waypoints and has an associated expected cost. Edges in the opposite direction of expected traverse are also added in case back tracking is required. Such planning allows for the inclusion of contingency paths into a single traversal command, potentially covering hundreds of meters.

B. Global Path Planning

This is the preliminary part of the rover execution of a traversal command. It uses the associated graph to identify the optimal path to the target based on expected costs. Waypoint Traversal is then iteratively executed, treating the next waypoint as the local target. At the end of each successful iteration, expected costs are replaced with actual costs, while failed traversal results in the corresponding edge being removed, and the current rover locations being added as new nodes that are connected to the last waypoint. The updated graph is then used to re-plan the global path.

C. Waypoint Traversal

Waypoint Traversal performs the core of the traversal actions based on a mode of navigation similar to the *motion-to-goal* and *boundary-following* behaviours described by Volpe et al in [1].

The rovers turns towards the next waypoint, facing along the potential straight line path. A high resolution digital elevation map is built, combining data from sensors on both rovers. Remote soil sensing results, where available, are integrated with geometric terrain characteristics to detect impassable terrain. A path suitable for the primary rover to the waypoint is calculated (or alternatively to the end of the available elevation map if the waypoint lies outside, with the rovers moving to the waypoint iteratively, and map extensions created when the mapped region is traversed).

If no direct path can be found due to detected hazards or an obstacle that was not visible in the planning data sets, the rovers can attempt to circumnavigate the detected hazard. This is achieved by the rovers turning away from the obstacle. However the rovers are permitted to turn only a limited amount in the circumnavigation efforts, preventing the rover from moving in a direction away from the waypoint. Once past the obstruction – or on reaching the end of the mapped region – the rovers turn towards the waypoint and restart the sense-plan-move cycle.

The scout rover then moves along the planned path, using its miniaturized sensor suite to assess trafficability. Once the scout rover has advanced, the primary rover follows deploying on-board sensors to verify trafficability. This approach is repeated until the waypoint is reached. When the scout rover reaches the end of the planned path, it turns towards the next waypoint and another pair of images from the navigation cameras is used to extend the elevation map. The extended map serves as input for another iteration of local path planning with the final location of the previous trajectory as a start point. One important constraint is that the scout rover always operates within in line of sight of the primary rover. This is essential as it allows a robust relative localization between the two rovers.

At any time, the FASTER SSS could reach a ‘NO-GO’ trafficability assessment resulting in the invalidation of the planned local path. If non-traversability is determined on the basis of the primary rover sensors, the scout rover returns to the primary rover and the planning of a new path is attempted. If the scout rover sensors trigger the negative assessment, an attempt is made to plan an alternate path for that segment. In this case, if no alternate path is found, two new nodes are added – corresponding to the locations of both rovers. Depending on the optimal global path found, either the primary rover proceeds to the location of the scout using the planned local path or the scout returns to the primary rover location. Similar actions are taken if no path can be found.

III. SCOUT ROVER

The scout rover serves the purpose of a mobile sensor platform in the proposed concept enabling the forward acquisition of terrain and soil characteristics. Designed to be able to safely traverse terrain that is hazardous to the mission rover (or primary rover), the proposed platform is a small, lightweight robot inspired by the DFKI robots ASGUARD [2] and CESAR [3], which won the 2008 ESA Lunar Challenge.

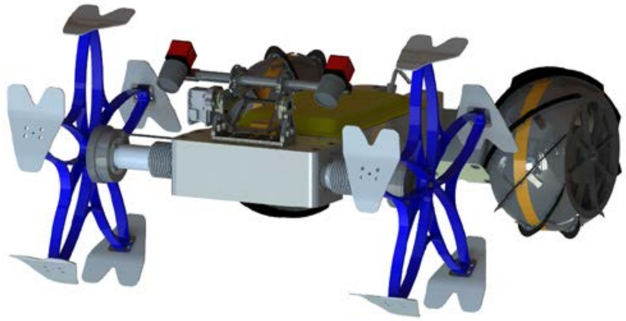


Figure 2. Scout Rover Design

It implements legged wheels as front wheels, a design that has shown to be provide excellent mobility in varied terrain ranging from rocky, hard terrain to softer sand-like. It provides for a better capability for traversing rock like obstacles than standard wheel designs without requiring a complex suspension system such as a rocker bogie, while at the same time avoiding the mechanical complexity and increased mass that is associated with a typical legged system. Each leg or wheel spoke will be fitted with feet to decrease the footprint pressure. The feet are designed with bent ‘toes’ that provide extra traction on softer terrain. Coupled with the legged wheels on the front, a passive joint along the roll axis in the chassis allows the rover to easily climb over obstacles that would cause problems for other ground vehicles of a similar size and complexity. The rear wheels are hollow wheels fitted with inclined grousers – enabling sideways motion and allowing the scout rover to turn on the spot.

Apart from the above mentioned reason of maintaining a low foot pressure, the scout rover was designed under strict mass and size requirements to enable it to be included in future planetary missions under current launcher and mission rover specifications. Due to such expected mission parameters, the scout rover is not designed to have complete power autonomy – an electrical power system capable of storing power for 4 hours of driving operations are foreseen, with the scout rover intended to dock with the primary rover to recharge its batteries. The initial scout rover design proposes the use of a dust resistant docking mechanism [4] developed at the DFKI within the RIMRES project.

Apart from the soil sensing payload, the scout rover has a stereo camera system as navigation sensors and wheel encoders and an attitude heading reference system (AHRS) for proprioception.

IV. SOIL SENSING SYSTEM

The Soil Sensing System (SSS) has been designed to provide terrain trafficability assessments and hazard detection prior to the primary rover traversal.

It comprises three categories of sensing capabilities:

1. Remote Sensing
2. Scout Rover Sensing
3. Primary Rover Sensing

While remote sensing focusses on the detection of visually recognizable hazards, as seen in Figure 4 the scout rover and primary rover sensors cover a comprehensive range of terrain hazards. Each sensing modality provides a trafficability classification for the analyzed region specifying if the terrain is traversable by the primary rover (‘GO’), is a potential hazard (‘NO-GO’) or is of unknown or unsure traversability (‘MAYBE’), with the SSS using a decision tree for data fusion.

A. Remote Sensing

Remote sensing capabilities focus on the analysis of imagery from the primary rover cameras for the detection of rocks based on semantic feature identification.

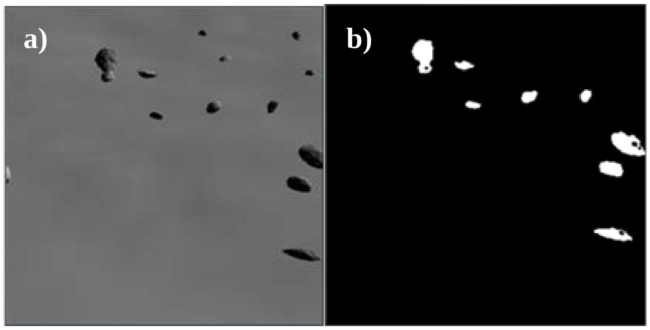
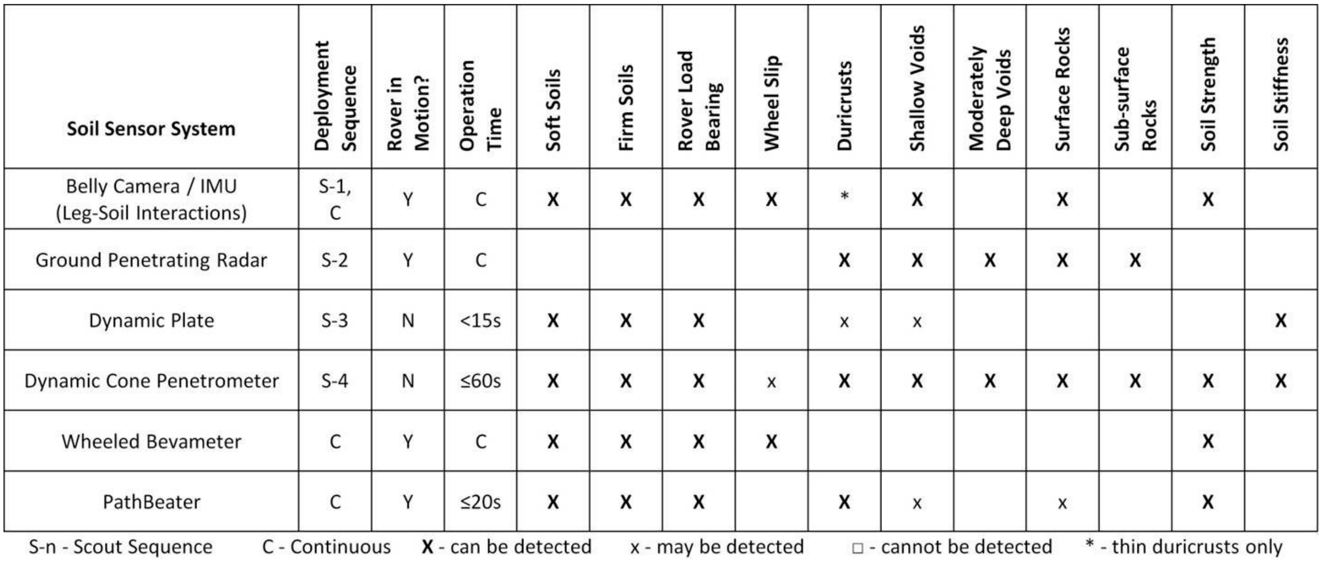


Figure 3. Blob Detection based remote sensing.
a) original image, b) thresholded image with largest blobs

The primary approach considered is based on blob detection, classification and tracking. The image from the primary rover is thresholded based on the histogram distribution, and the largest blobs are extracted. Each of these blobs is indexed, and characterized using contours,



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	X
Wheeled Bevameter	C	Y	C	X	X	X	X						X	
PathBeater	C	Y	≤20s	X	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

Figure 4. Summary of soil sensor capabilities

bounding boxes and Hu moments. Based on these characteristics, the indexed blobs are matched with blobs from the previous image, with outliers being rejected on the basis of estimated position change.

Apart from blob detection based sensing, supervised machine learning classifiers and saliency detection (based on colours, intensity and orientation) are also considered.

B. Scout Rover Sensing

Scout rover sensing is based on a suite of four miniaturized soil sensors: Scout Leg-Soil Interaction, Ground Penetrating Radar, Dynamic Plate and Dynamic Cone Penetrometer. A novel design for a hybrid Dynamic Plate and Dynamic Cone Penetrometer with a common electric drive, similar in design to the Planetary Underground Tool (PLUTO) [5], has been developed, thus reducing the mass of the sensor suite. The sensors are deployed in a hierarchical order, with the next sensor (in terms of complexity and measurement time) being deployed only if no definite trafficability assessment can be made. This is done to allow the soil sensor suite to provide continuous assessment of trafficability, stopping the scout rover only when necessary.

Scout Leg-Soil Interaction: Two different methodologies are used to analyse the interaction of the scout leg and the soil. An inertial measurement unit will be deployed to estimate the impact force of the leg on the surface. A camera placed under the scout rover chassis will attempt to capture the sinkage of the leg, using computer vision techniques based on colour thresholding to measure the depth of sinkage.

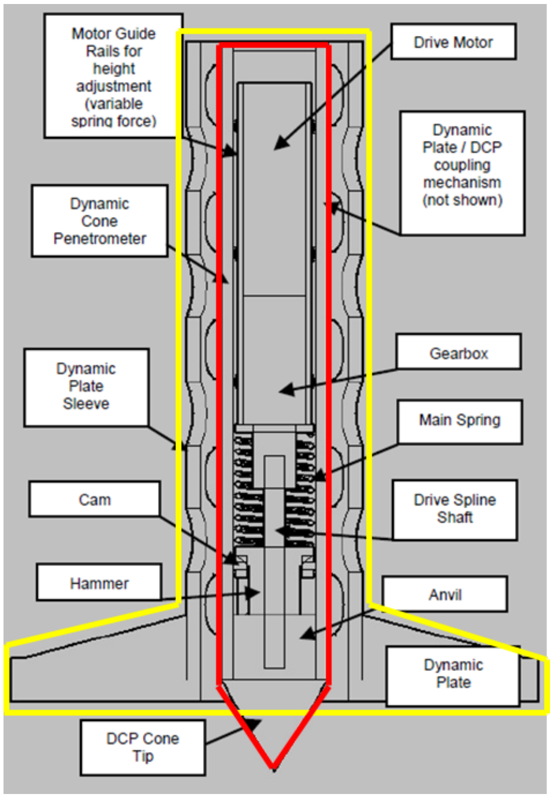


Figure 5. Hybrid DP – DCP Sensor (DP outlined in yellow, DCP outlined in red)

Ground Penetrating Radar (GPR): A GPR is extremely valuable as it allows the detection of boundaries between different soil strata, enabling the characterization of subsurface hazards such as voids. Additionally, the data from the GPR would be of great scientific benefit.

Dynamic Plate (DP): The sensor utilizes the drive mechanism to press a plate against the surface, attempting to recreate the same load on the terrain as would be applied by the primary rover. The soil compressibility under the load is used to estimate traversability.

Dynamic Cone Penetrometer (DCP): The sensor utilizes the drive mechanism to repeatedly hammer a conical tip against the surface, measuring the tip resistance and penetration depth. Deployment requires decoupling the plate from the drive mechanism. Requiring repeated blows increases the operation time, however penetration of the surface enables detection of subsurface hazards.

C. Primary Rover Sensing

Primary rover sensing is based on an additional sensor mounted at the front of the primary rover. This allows for continues forward trafficability analysis in case of scout rover failure. Two sensors are currently considered for this purpose: a wheeled bevameter and a 'PathBeater'.

Wheeled Bevameter: A commonly used sensor for terrestrial trafficability analysis, this method has been applied to data from the MER rovers to analyse Martian surface properties [6]. An instrumented test wheel deployed in front of the rover that provides representative terrain loading is foreseen. Based on the observed wheel rut depth and calculated wheel slip, Bekker parameters can be estimated, and used in well-known mobility models to calculate terrain trafficability.

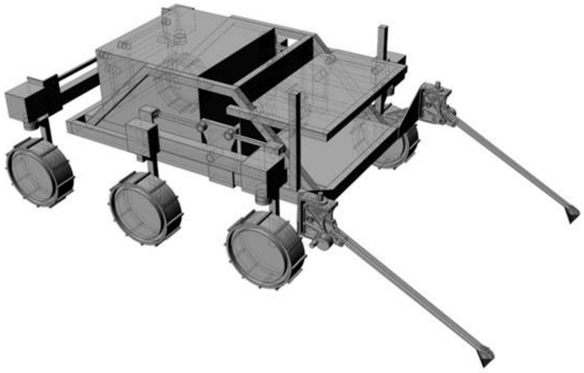


Figure 6. PathBeater depicted mounted on Bridget platform

PathBeater: A novel sensor concept, it comprises two arms with pyramidal penetrators at the tips mounted on top of the rover wheels. Actuated to periodically impact the ground, it uses inertial sensors and strain gauges to estimate the bearing strength. The penetrator tips are then pushed along the ground for a short while, allowing the measurement of shear strength.

V. COOPERATIVE AUTONOMY

The system targets collaborative traversal based on a partial implementation of the ECSS E4 level of autonomy [7] allowing “execution of goal oriented mission operations on-board”.

In an attempt to reduce the demands on the power budget of the scout rover, the system autonomy resides on the primary rover, with the scout rover treated as a mobile sensor capable of path following and capable of following a path provided to it by the primary rover as well as basic health monitoring.

The software subsystems for the primary rover have been implemented using a combination of the popular Generator of Modules (G^{en}oM) and Robotic Operating System (ROS) frameworks. The G^{en}oM [8] framework, previously deployed as a framework for planetary rovers as described in [9], is used to define the software subsystems interfaces and handle communication between the subsystems. The subsystems themselves are designed to leverage the popularity of the ROS framework [10], enabling quick prototyping of functionality through the re-use of open source algorithmic implementations.

Figure 7 shows the software architecture for the primary rover, identifying the software subsystems.

Task Planner: A symbolic task planner supporting goal based planning of tasks and contingency actions for both rovers. It is one of the key subsystems for cooperative autonomy. Based on Hierarchical Task Networks [11], the planner can consider multiple concurrent tasks, building an interleaved plan that is validated against available resources.

Health Management: A representative fault detection and recovery subsystem based on offline analysis of potential faults and the corresponding indicators and corrective actions.

Task Execution Controller(s): On-board procedure execution engines supporting the execution of pre-defined sub-tasks.

GNC: The Guidance, Navigation and Control subsystem performs all the path planning, mapping and self-localization tasks for the primary rover, and as such it is one of the key subsystems for cooperative autonomy. The mapping module should be able to produce detailed maps of the terrain from multiple point clouds (stereo image pairs), given good estimates for the relative positions. Self-localization is based primarily on odometry, wheeled or inertial, and visual. A Simultaneous Localization and Mapping approach using the detected rocks (from remote sensing) as features is being implemented, and an approach to match the local maps to lower resolution orbiter maps is being studied. Path planning operations include manipulation of the global path graphs, as well as D* path planning using the high resolution elevation maps generated, and trajectory fitting for the primary rover to the planned path.

Data Management: A representative data handling subsystem which is responsible for dispatching and maintaining shared data between the subsystems, as well as preparing telemetry for transmission.

Scout Localization: A computer vision subsystem to localize the scout rover in camera images, allowing drift free localization of the scout rover, it is one of the key subsystems for cooperative autonomy. Two approaches

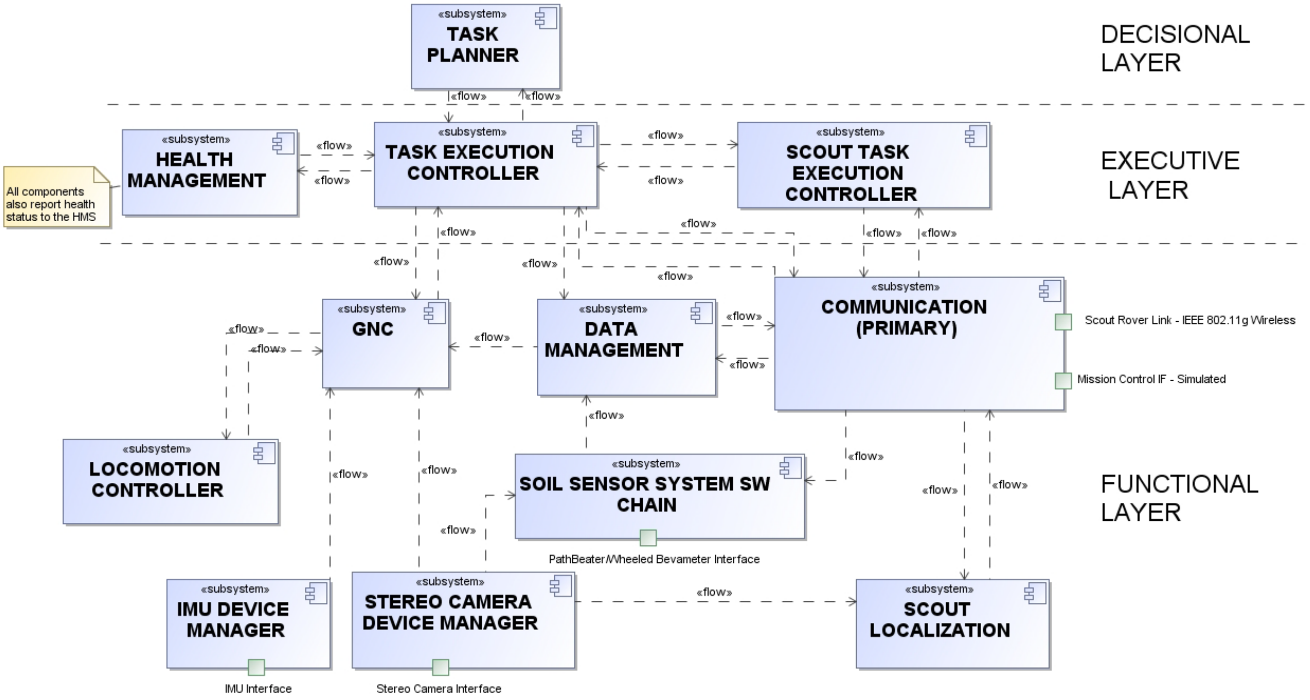


Figure 7. Primary Rover Software Architecture

are currently considered: marker tracking and point feature tracking. Marker based tracking estimates the scout pose using distinctive pattern that is rigidly attached to the scout. Apart from a single marker which can be occluded, the performance using a cubic structure with multiple markers (one on each visible face) will also be benhmarked. These will be compared to the performance using Speeded Up Robust Features (SURF) [12] point descriptors to identify the scout by comparison against a database of descriptors identifying the scout.

Soil Sensor System SW Chain: Subsystem interfacing and implementing parts of the FASTER SSS software, able to provide classified trafficability results.

Communication: Subsystem responsible for communication between the rovers, as well as providing representative functionality for communication with mission control.

Locomotion Controller: A motion controller for the primary rover, capable of following simple paths and trajectories that have been planned by the GNC.

Device Manager(s): Subsystems providing interfaces to various primary rover sensors.

VI. SYSTEM VALIDATION

System components will be validated through a series of unit tests before integration tests culminating in a field trial. For the purposes of system validation, the Bridget locomotion platform [13] from EADS Astrium UK will be used as the primary rover.

Figure 8. Bridget Locomotion Breadboard [Photo: PRoVisG field trial, Tenerife, 2011]

The scout rover will undergo a number of locomotion and hardware tests using laboratory setups replicating specific terrain conditions. Individual soil sensors, except for remote sensing algorithms, will be calibrated and tested using well characterized soil simulants. The remote sensing algorithms will be validated using terrain imagery generators such as Pangu.

While individual autonomy components will also be tested using representative data sets, testing of autonomy will primarily be performed using the Gazebo simulation environment [14]. Gazebo is a popular mobile robot simulator that has been selected as the simulation environment for the DARPA Virtual Robotics Challenge to be held in June 2013. Simulation environments will be based on data from High Resolution Imaging Science Experiment on the Mars Reconnaissance Orbiter [15] .

The field trial and final system validation is expected to take place in the second half of 2014.

Figure 9. Scout rover in Gazebo on simulated Mars terrain

REFERENCES

[1] R. Volpe, T. Estlin, S. Laubach, C. Olson, and J. Balaram. “Enhanced mars rover navigation techniques,” In *Proc. IEEE International Conference on Robotics and Automation, 2000* (ICRA'00), IEEE, Vol. 1, pp. 926-931.

[2] M. Eich, F. Grimminger, and F. Kirchner, “A Versatile Stair-climbing Robot for Search and Rescue Applications,” in *Proc. 2008 IEEE International Workshop on Safety, Security and Rescue Robots*, Sendai, Japan, 2008.

[3] J. Schwendner, F. Grimminger, S. Bartsch, T. Kaupisch, J.B. Akpo, A. Bresser, M. Yüksel and M.K-G. Seydel, “CESAR: A Lunar Crater Exploration and Sample Return Robot,” in *Proc. 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, St, Louis, USA, 2009.

[4] W. Wenzel, F. Cordes, A Dettmann and Z. Wang. “Evaluation of a Dust-Resistant Docking Mechanism for Surface Exploration Robots,” in *Proc. 15th International Conference on Advanced Robotics (ICAR)*, Tallinn, 2011.

[5] L. Richter, P. Coste, V. Gromov, H. Kochan, S. Pinna, and H-E. Richter. "Development of the “planetary underground tool” subsurface soil sampler for the Mars Express “Beagle 2” lander." *Advances in Space Research* 28, no. 8 (2001): 1225-1230.

[6] K. E. Herkenhoff, M. P. Golombek, E. A. Guinness, J. B. Johnson, A. Kusack, S. Gorevan, L. Richter, and R. J. Sullivan (2008). Chapter 20: In Situ Observations of the Physical Properties of the Martian Surface. In: Jim Bell (ed.). *The Martian Surface: Composition, Mineralogy, and Physical Properties*. Cambridge University Press.

[7] ECSS, “Ground Systems and Operations – Telemetry and Telecommand Packet Utilisation,” *ECSS-E-70-11*, ESA Publications, January 2003.

[8] S. Fleury, M. Herrb and R. Chatila. “GenoM: A Tool for the Specification and the Implementation of Operating Modules in a Distributed Robot Architecture,” In *Proc. International Conference on Intelligent Robots and Systems*, pages 842-848. Grenoble (France), 1997.

[9] A. Ceballos, L. De Silva, M. Herrb, F. Ingrand, A. Mallet, A. Medina and M. Prieto, “GenoM as a Robotics Framework for Planetary Rover Surface Operations,” in *Proc. 11th ESA Workshop on Advanced Space Technologies for Robotics and Automation*, Noordwijk, The Netherlands, 2011.

[10] Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T., Leibs, J., Wheeler, R. & Ng, A.Y. (2009). ROS: an open-source Robot

Operating System. In *Proc. IEEE International Conference on Robotics and Automation (ICRA), 2009: Workshop on open source software*, IEEE, Vol. 3, No. 3.2.

[11] 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*, Turin, Italy, 2012.

[12] Bay, H., Tuytelaars, T., & Van Gool, L. (2006). Surf: Speeded up robust features. In *Computer Vision–ECCV 2006*, Springer, Berlin/Heidelberg, Germany, pp. 404-417.

[13] C. Lee, J. Dalcolmo, S. Klinkner, L. Richter, G. Terrien, A. Krebs, R. Siegwart, L. Waugh and C. Draper, “Design and manufacture of a full size breadboard ExoMars Rover chassis,” in *Proc. 9th ESA Workshop on Advanced Space Technologies for Robotics and Automation*, Noordwijk, The Netherlands, 2006, pp. 28–39.

[14] Koenig, N., & Howard, A. (2004). Design and use paradigms for Gazebo, an open-source multi-robot simulator. In *Proc. IEEE/RSSJ International Conference on Intelligent Robots and Systems, 2004*, IEEE, Vol. 3, pp. 2149-2154.

[15] Zielinski, S. (2007). Mars imagery now available on the Web. *Eos, Transactions American Geophysical Union*, 88(26), 270.