Multi-Level Soil Sensing Systems to Identify Safe Trafficability Areas for Extra-Planetary Rovers*

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A handful of robotic exploration rovers have had successful landings and missions on Mars. These missions, however, were not without issues. The Mars Exploration Rovers (MER) *Opportunity* and *Spirit*, for example had several difficulties in traversing the terrain; and *Spirit's* mission ultimately ended due to becoming permanently embedded in soft soil. To alleviate this issue with future extra-planetary missions, a multi-level soil sensing system approach is being developed that will allow rovers to assess the trafficability of the soil. This approach uses several sensor systems with overlapping areas of detection for data correlation and fault redundancy; allows for rapid, cursory data collection while the rover is in motion; and can also provide highly-detailed soil characteristic information while the rover is stopped. Combining these systems on a highly-mobile scout rover that can survey potential travel routes ahead of a larger primary rover reduces the risk of the more-important primary rover, which also has its own soil sensors, becoming incapacitated due to untrafficable terrain.

Four soil sensor systems are being investigated for inclusion on a small scout rover: a belly camera, inertial measurement unit (IMU), and motor monitor system to observe leg-soil interactions; a small ground penetrating radar (GPR) unit; a dynamic plate (DP) that replicates the pressure loading of a primary rover wheel on the terrain; and a dynamic cone penetrometer (DCP) (Fig. 1) based on a conventional terrestrial civil engineering tool to gather more-detailed soil characteristic data. These systems will be activated sequentially, with the camera/IMU system operating continuously. The primary rover will also have its own soil sensors, both to provide additional data and as a safety system should the scout rover fail. These systems are a wheeled bevameter (WB) and PathBeater (PB), each of which can operate continuously. Sensor activation sequences, detection abilities, operating conditions, and operating times, are shown in Table I.

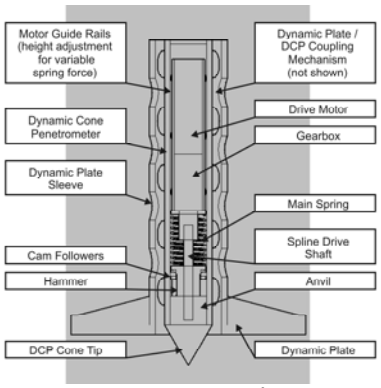

Figure 1. Hybrid dynamic plate/dynamic cone penetrometer design

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			

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

Table I. Sensor detection and operational characteristics matrix

Each of the soil sensor systems generates a '% Trafficability' numerical result and a trinary assessment of 'GO', 'MAYBE', or 'NO-GO'; except the DCP which can only yield a binary 'GO' or 'NO-GO'. These results are then combined into a data fusion system to be incorporated into the primary rover's navigation system. If the trafficability results of any of the sensor systems are 'MAYBE', the subsequent sensor system will be deployed until one of them generates a 'GO' or a 'NO-GO' result. After this, the process repeats from the start with only the initial sensor system active.

Currently, prototype systems for the vision processing of the leg-soil interactions, dynamic plate design, and the dynamic cone penetrometer design are being tested in laboratory conditions.Sensor system designs and initial laboratory test results are presented within this paper. The project will ultimately develop a set of integrated prototype hardware and software systems for each of the sensor systems and both the scout and primary rovers and will participate in coordinated field test demonstrations.

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