Multi-level soil sensing systems to identify safe trafficability areas for extra-planetary rovers

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MULTI-LEVEL SOIL SENSING SYSTEMS TO IDENTIFY SAFE TRAFFICABILITY AREAS FOR EXTRA-PLANETARY ROVERS

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ABSTRACT

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*, as examples, had several difficulties in traversing the terrain; and *Spirit's* mission ultimately ended due to becoming permanently embedded in loose soil. This paper describes the development of multiple sensor systems on a highly-mobile scout rover with overlapping areas of detection for data correlation and fault redundancy; allowing for collection of both rapid, cursory data while the rover is in motion and highly-detailed soil characteristic information while the rover is stopped. The mission-critical primary rover will also possess its own direct and remote sensing systems for added mission safety.

1. INTRODUCTION

The continued interest in extra-terrestrial exploration has led to several robotic missions to Mars. These rovers have provided great insight into the planet, but each has faced difficulty with traversing the Martian surface. Both of the MER rovers, *Opportunity* and *Spirit*, each became trapped in the soft, underlying soil [1]. *Opportunity* was able to be navigated away from its hazardous soil; however, *Spirit* was not so fortunate and it remains lodged in the soil at the location known as "Troy" [2].

To address these hazardous terrain issues, the Forward Acquisition of Soil and Terrain data for Exploration Rover (FASTER) project (an EU-funded, FP7 multi-partner collaboration) is developing a two-rover team formed by a small scout rover that can survey and assess the trafficability of the surface [3], thereby minimising the risk of becoming immobile for the larger, mission-performing rover. The scout rover is designed with five-spoked, rim-less wheel-legs that allow it to traverse hazardous terrain, such as soft soils and obstructing rocks.

In order to assay the soil, the scout is equipped with an array of soil sensor systems (developed by the University of Surrey(1)): a leg-soil interaction observation system to determine soil bearing ability and detect leg slip; a ground penetrating radar unit to detect duricrusts and subsurface hazards; a dynamic plate to replicate the bearing pressure of a primary rover wheel; and a dynamic cone penetrometer to assay soil properties both at and beneath the surface. These sensor systems have overlapping areas of detection and vary in their deployment and operation times. To maintain rapid traverses, systems that allow the scout rover to remain in motion are used first, while more-detailed systems that require the scout to stop are used when the more rapid systems provide inconclusive information on the safety of the soil. This hierarchical deployment concept provides a high level of safety while also maintaining rover movement whenever possible. The sequential deployment of the sensor systems also minimises the power consumption of the rover, as each system is operated independently and not simultaneously.

In addition to the host of sensor systems on the scout rover, the primary rover is also equipped with its own means of trafficability analysis (developed by LIQUIFER Systems Group(2)). While the primary rover will be equipped with a single sensor system, two systems are being developed as candidates. The first is a wheeled bevameter that will analyse the load bearing and shear properties of the terrain before primary rover. The other is a novel concept called PathBeater and it includes two arms with penetrometer tips that cyclically impact the soil in front of its wheel paths and infers mechanical properties of the soil.

Each of these sensor systems is able to provide a trafficability assessment to the navigation system as a numerical confidence value and as a trinary state of: GO, MAYBE, or NO-GO. For the scout rover, sensor system assays that yield a MAYBE initiate the next sensor system in the sequence, for a more-detailed soil analysis.

The purpose, function, and development of each of these sensor systems are described in detail throughout the paper. They are currently being developed independently, but will be integrated into the scout and primary rovers in early 2014. Tab. 1, describes the detection and operation features of each of the sensor systems.

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 1. Scout and primary rover soil sensor systems detection and operational characteristics matrix.

2. SCOUT ROVER SOIL SENSOR SYSTEMS

2.1. Leg-Soil Interaction Observation

Several integrated components comprise the leg-soil interaction observation system: a camera, a scout rover-mounted IMU, wheel-leg encoders, a motor current sensor, and a specially-designed foot.

The camera observes the lower half wheel-leg such that the hub and the reach of the legs can be imaged. The IMU records chassis movements of the scout rover in order to identify ground reaction forces and soil interaction accelerations, with the aim of characterising soil hardness and locating duricrusts that the wheel-leg can puncture. A 2-channel quadrature wheel encoder has been augmented with a reflective IR emitter-receiver pair to act as an indexing source, which provides the sensor system with absolute position information of the wheel leg; this allows the exact angle of each leg to be known. Motor torque is measured by means of a current sensing module, in order to determine slip conditions. Each of the sensors is interfaced with an mbed microcontroller for data capture and processing. The camera interface and image processing will be handled by a Raspberry Pi Model B.

The camera-based observations of the leg-soil interactions are used to determine the amount of sinkage that a leg experiences. This is facilitated by a specially-designed Load Testing Foot (LTF) (Fig. 1). The LTF is designed to replicate the force concentration of the larger, primary rover in a scaled-down manner for the smaller, lighter scout rover. The scaled-down loading allows the scout rover to have similar amounts of sinkage to the primary rover. In order to ensure the safety of the scout rover, only two of the five legs are equipped with the LTF; the remaining legs have highly-capable feet that provide enhanced mobility.

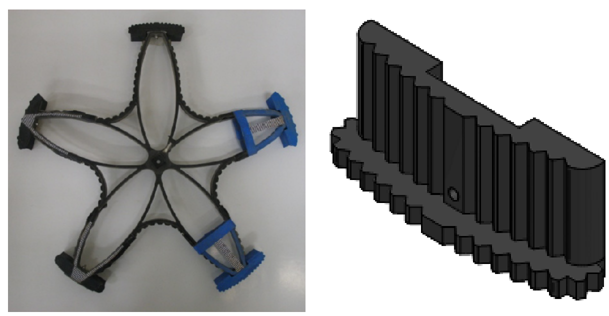

Figure 1. Wheel-leg used for lab testing with multiple Load Testing Feet attached (left). Close-up rendering of a single Load Testing Foot (right).

A vision-based leg sinkage detection algorithm correctly segments the contour of the leg from the background and from deformable terrain by having the wheel constructed from blue material (blue tape is used in the initial laboratory experiments, see Fig. 1), which enables us to perform accurate and robust colour space segmentation [4] of the wheel (Fig. 2(1) and Fig. 2(2)). Additionally, an integrated wheel-leg encoder is used to compute the pose of the leg such that anything that lies outside the Region of Interest (ROI) is masked (Fig. 2(3) and Fig. 2(4)). Detection of the wheel contour is achieved by performing a low-order moments [5] analysis on the masked binary image whereby the area of all detected contours are computed from the Zeroth moment and the largest blob is selected. Finally, the sinkage is calculated by measuring, in pixels, the level of occlusion on the leg by the deformable terrain and converting the value to millimetres. Tests conducted thus far indicate that the algorithm is robust to lighting, shadowing, and background objects and gives an average relative error of 2.5mm [7.2%] from the measured sinkage via a linear position transducer (a measurement device that is part of the test rig, and not the leg-soil interaction observation sensor system) that is attached to the wheel hub and has an accuracy of ±1mm.

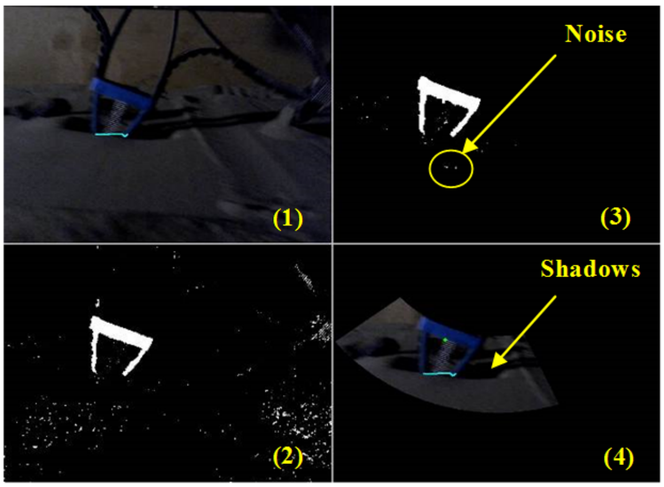

Figure 2. Processed image from the proposed vision based algorithm for the poor lighting conditions scenario. Luminance = 10-50 Lux.

Several in-lab experiments have been conducted to gather leg-soil interaction data for each of the parameters mentioned previously: wheel-leg orientation; motor current; an absolute measure of leg sinkage via a linear transducer; IMU data; and video information that was used for off-line analysis. These tests were performed in a Single Wheel-Leg Test Bed (Fig. 3) with a motorised carriage that propels the wheel-leg along its length. The wheel-leg is attached to the carriage via linear bearings that allow free vertical movements. The tests were performed with an array of operating parameters that varied the wheel-leg motor speed relative to the carriage speed (in order to cause slip or no-slip conditions), the mass of the wheel-leg system (to simulate different masses of the under-development scout rover), and the lighting and background conditions (to test the robustness of the vision system).

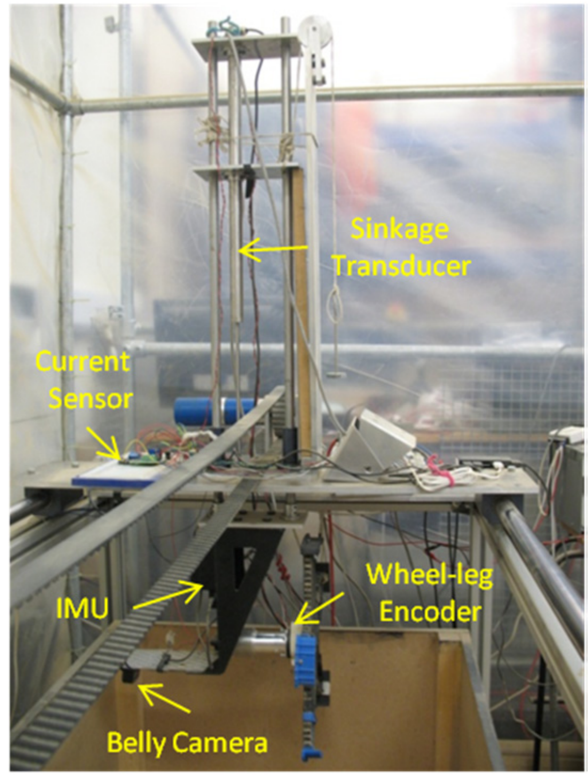

Figure 3. Single Wheel-Leg Test Bed for evaluation of the leg-soil interaction observation sensor system.

2.2. Ground Penetrating Radar

A ground penetrating radar (GPR) unit will be implemented that is based on the MINEHOUND unit developed by Cobham, PLC (Cobham, PLC, Wimborne, Borset, United Kingdom). The product version of the unit encompasses a GPR unit and metal detector in a lightweight, portable package. The GPR portion of the unit uses frequencies of 500MHz to 3GHz to detect subsurface features and objects. For the purposes of FASTER, only the GPR portion of the unit will be utilised, and will only operate at the 3GHz frequency. This high end of the operating frequency range has a wavelength of 100mm, which will provide a resolution of 25mm (1/4 wavelength). This resolution will be sufficient for detecting medium-thickness duricrusts and subsurface features, such as voids and rocks.

Preliminary simulations have been conducted of the GPR unit for a variety of soil types, layer thicknesses, and the presence of sub-surface voids (Fig. 4). Additional research is currently being conducted in simulating soils that contain representative compounds that have been identified by previous Mars missions, from the early Viking missions through to the current Martian rovers.

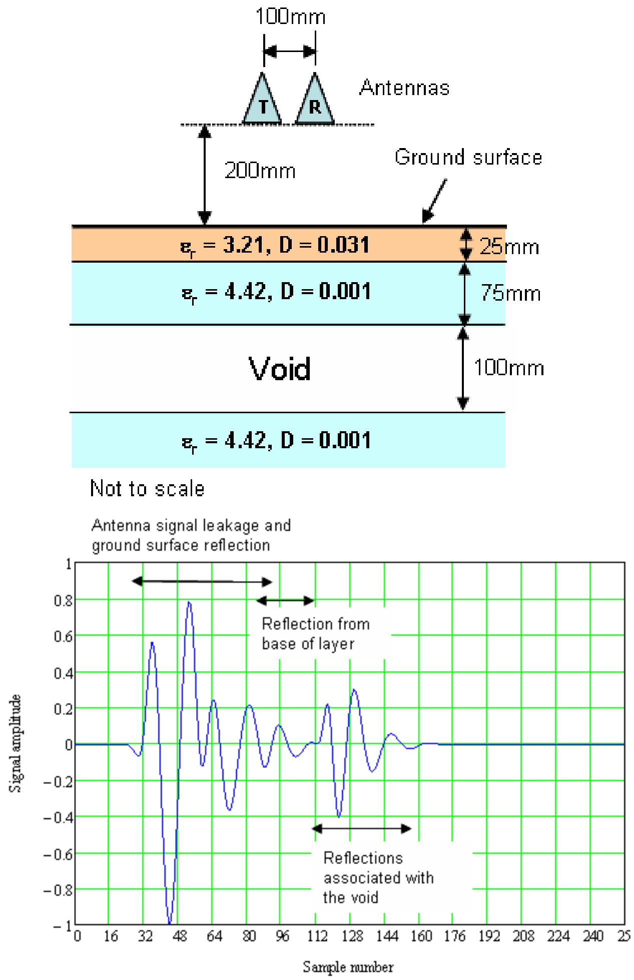

Figure 4. Ground Penetrating Radar simulation results utilising two soil types in three layers and the presence of a sub-surface void residing between two layers of similar soil.

2.3. Hybrid Dynamic Plate and Cone Penetrometer

Two of the scout sensors have a similar drive mechanism. Both the Dynamic Plate (DP) and the Dynamic Cone Penetrometer (DCP) utilise an impact device that propels the instrument into the soil. The impact device is required as the small, lightweight scout rover has insufficient mass to apply a large, constant force to the sensors, which is how they are often used for terrestrial surveys. Combining the two sensors together also saves space and mass when integrated into the scout rover (Fig. 5).

The dynamic plate is used to test the ability of the soil to support the load of the primary rover. The plate dimensions (124mm O.D., 40mm I.D.) mimic the contact patch area of a single wheel from the primary rover. While normally a plate sensor is a solid disk, we have placed a hole in the centre to allow free passage of the DCP. The DCP houses the impact drive mechanism and is connected to the outer shroud of the DP via a spring-locked, electrically released coupling mechanism. Slightly smaller than a standard cone penetrometer, our DCP has an outer diameter of 30mm and an internal cone angle of 60 degrees. A 9-axis inertial measurement unit (IMU) is embedded within the DCP between the anvil and the cone. The IMU measures rotational, longitudinal, and magnetic forces on the device and is used for depth measurements, monitoring impact forces, and recording soil resistance.

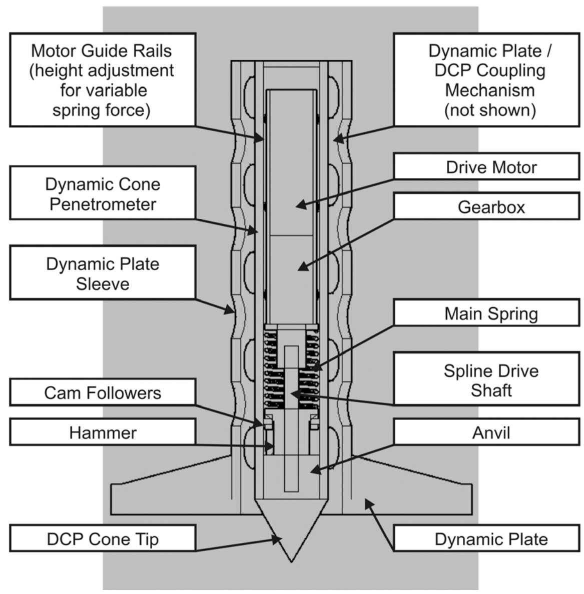

Figure 5. Initial Hybrid Dynamic Plate and Dynamic Cone Penetrometer design with a common impact drive mechanism.

The drive mechanism is an impact device that repeatedly strikes a hammer into an anvil. The hammer has three connected sloped surfaces around its perimeter that are contained by three small cams. A drive motor and gearbox rotate the hammer via a ball spline, which applies torque but allows free movement along the axle. When rotated, the hammer slopes engage the cams and cause the hammer to compress the drive spring. The sloped surfaces have steep faces that precede the beginning of the next slope feature, which allow the spring to freely apply its force to the hammer (now unconstrained by the cams) and send it into the anvil. This process repeats as the hammer is rotated by the drive motor. The drive motor has a high torque/low speed gearbox that provides approximately one impact per second (three impacts per full revolution of the hammer).

A second motor and gearbox will be used to move the position of the drive motor along the length of the sensor in order to adjust the pre-load on the drive spring. This adjustment will allow the drive mechanism to apply the required force for each operating mode: DP and DCP. The position of the hammer, cams, and anvil are unaffected by this movement.

Control of the hybrid sensor is handled by an mbed microcontroller. It is responsible for activating the drive motor and spring tension adjustment motor via speed controllers. It is also responsible for interfacing with the IMU device, via an I^2C interface, and reading encoder information from the drive and spring tension adjustment motors. The data gathered from the IMU is processed on the microcontroller to create depth-per-blow and blows-per-depth information, which is used in the soil trafficability assessment. The post-process results from the sensor consist of a trafficability evaluation, indicated as a percentage, and a trinary flag of GO, MAYBE, and NO-GO based on threshold values of post-process results.

The final design is still being fabricated; however, manual drop mass tests have been conducted in the laboratory with similarly-designed, yet independent, DP and DCP devices. The devices share the same body, drop mass, and guide rod for the mass, but have interchangeable sensor ends: one for the DP and one for the DCP (Fig. 6).

Figure 6. Early Dynamic Cone Penetrometer (left) and Dynamic Plate (right) instruments with a manual dropped mass. The DP sensor end (right) replaces the DCP cone shown in the left image to share a common impact mechanism.

A 1kg mass is dropped from two separate heights, depending on the sensor end that is attached, in order to generate the appropriate impact force. For the dynamic plate, a 720N force is used, which approximately applies a $45kN/m^2$ pressure to the soil. This is 150% of the pressure exerted by a single primary rover wheel, and the additional 50% pressure is our large margin of safety. The dynamic cone penetrometer relies on a much lower impact force of approximately 239N, which has been observed to generate satisfactory penetration depths with each impact. If the DCP impact force were too low, the sensor would require many more impacts than necessary to reach the target sensing depth of 200mm, as defined in the project specification. Conversely, if the force were too high, the DCP would penetrate too far with each impact and there would be a loss of data resolution in characterising the reaction of the soil.

Two types of soils have been used for the previous laboratory tests: ES-3, a coarse quartz-based sand with a grain size of approximately 800µm; and SSC-2, a fine crushed garnet powder with a grain size of approximately 50µm. The particles of the ES-3 soil are sub-rounded and provide a lower resistance to penetration than the fine-grained SSC-2; the SSC-2 granules are sub-angular. Tests have been conducted independently in these two soils with a variety of semi-uniform densities.

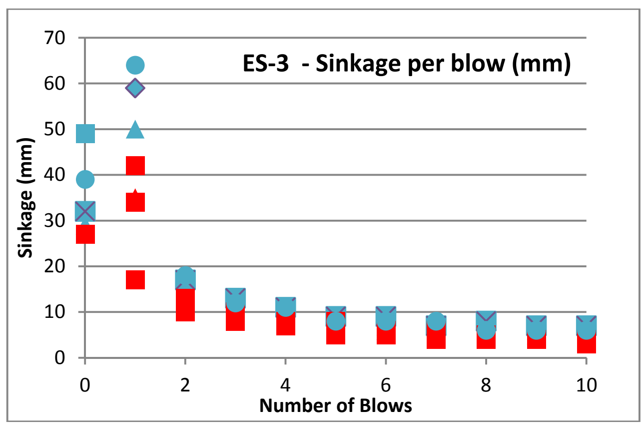

Figure 7. Laboratory Dynamic Cone Penetrometer tests with a manual dropped mass for ES-3 soil. Data trends show that the first two impacts yield the most unique data for each soil preparation. Blue markers indicate loose soil preparations; red markers indicate dense soil preparations.

Dynamic Cone Penetrometer tests began with the cone sinking into the soil under its own weight. Impacts were then applied until a penetration depth of 200mm was reached. As Fig. 7 shows, the first two impacts yield the most unique information about each of the soil preparations. Subsequent impacts to a depth of 200mm asymptotically approach 1-3mm per impact, independent of the soil density.

Similar manual dropped mass tests in a variety of ES-3 and SSC-2 density preparations have also been conducted with the DP. While the DP tests provided different depth-per-blow data, they also showed a similar asymptotic convergence when more than 2-3 impacts were administered.

3. PRIMARY ROVER SOIL SENSOR SYSTEMS

3.1. Wheeled Bevameter (WB)

The WB is conceived according to the terrain properties estimation method used on the NASA MER rovers [6][7] with the primary difference being that for FASTER it would follow a real-time approach (and use a dedicated test wheel), rather than being an off-line method. A dedicated measurement wheel (‘test wheel’) is used to load the terrain (from natural weight of the deployed test wheel assembly.) for acquiring the needed terrain and vehicle-terrain interaction parameters. The test wheel is arranged such that it protrudes in the rover driving direction. It is not a driving wheel, i.e. it is not powered.

The WB includes a placement mechanism for the test wheel and would be stowed until after landing on Mars. It is expected that the test wheel would remain lowered onto the ground during nominal rover motion, including when climbing and descending slopes. During normal operations, the placement mechanism assumes the function of a passive suspension of the test wheel, allowing the wheel to follow the terrain contour (including rolling over rocks and climbing as well as descending slopes of up to 25 degrees) (Fig. 8, top). Friction dampers are used in some of the mechanism joints to limit oscillations of the suspension in rough terrain. The system is capable of autonomously detecting test wheel ’stalls’ against rocks exceeding the wheel obstacle climbing capability (Fig. 8, bottom), permitting an autonomous raising of the test wheel off the surface, using the placement mechanism active joints, and its subsequent re-placement.

Quantities measured with the system for terrain properties retrieval are: test wheel sinkage (through a laser sensor), test wheel vertical load, test wheel horizontal reaction force and test wheel rotation rate. Measurements are performed at a rate of 10Hz while the rover is in motion. Measured test wheel rotation rate is continually processed with rover wheel rotation rates to obtain real-time estimates of rover slip which, together with measured test wheel sinkage and vertical load, are fitted in real-time to a wheel-soil model to yield terrain bearing strength and the associated Bekker / Wong parameters [8]. A brake accommodated on the test wheel is applied at regular intervals while the rover continues driving, in order to incur local terrain shearing under the test wheel which leads to a resistive force measured by the horizontal force sensor. This signal is processed along with slip estimates to yield the Bekker / Wong shear strength parameters

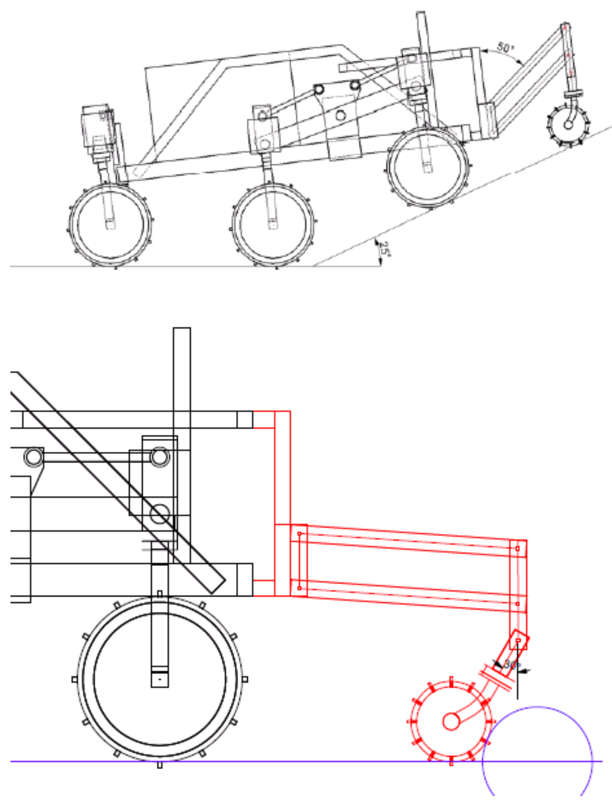

Figure 8. Wheeled Bevameter (test wheel and suspension) in deployed configuration in front of rover, seen during climb of 25° slope (top) and during traversal of a rock (bottom) (rover moving from left to right)

With the parameters thus determined on-line while the vehicle is in motion, mobility performance of the rover can be propagated forward and an assessment derived on the safety of continued mobility.

A mechanical mock-up of the WB has recently been built and evaluated successfully with respect to the terrain-following capability of the test wheel suspension (Fig. 9). The detailed design – mechanically and electrically – of the fully functional demonstrator is in progress, to be evaluated in field testing on the ‘Bridget’ rover vehicle (the primary rover testbed) from early 2014 onwards.

Figure 9. Mechanical mock-up of WB undergoing functional testing (LSG, V. Eder)

3.2. PathBeater

PathBeater is a new and unconventional soil sensing device. Its purpose is to determine the Martian surface bearing strength in advance of the path of a rover to ensure that the path is safe to traverse. In particular, its twin arms measure soil properties immediately forward of the front wheels and can detect soft surfaces likely to lead to the problems faced by NASA's Mars Exploration Rovers, *Spirit* and *Opportunity*. A fully functional prototype of PathBeater is currently being developed within the FASTER project and has entered the test phase.

PathBeater comprises two arms, each fitted with a penetrator, located above and aligned longitudinally with the wheels of the rover (Fig. 10). Although shown here fitted to the test rover, the sensor's basic dimensions can be scaled to match the size of other Martian rovers or even those that could be deployed on the lunar surface.

Each of the sensors arms are stowed and latched against the front of the rover during launch and landing and, when not required, during the surface exploration or sample retrieval missions. The arms are deployed simultaneously by a spring and an electrically-driven cam from their extended position, rotation of the cam releasing the energy stored in the spring which whips the arm to hammer the penetrator at the end of the arm into the Martian surface. The arm itself is fitted at its tip with a chip-type IMU, which contains gyros and accelerometers to measure local vertical accelerations, and along its length with strain gauges to measure bending deflections. The arms' deflections together with the IMU data allow an assessment of soil bearing strength. Since the measurements are made while the rover is in motion and with the arms still in their deployed positions they also lead automatically to a measurement of soil shear strength as the penetrometers are pushed through the surface before they are raised from their deployed to their extended positions by further rotation of the cams. The measurements from the two arms will also allow an assessment of soil characteristics across the path of the rover. The arms can be timed to be deployed at defined time intervals or can be operated continuously. The time required for sensor deployment, measurement and retraction is approximately 20s during which time the rover will have travelled about 350cm.

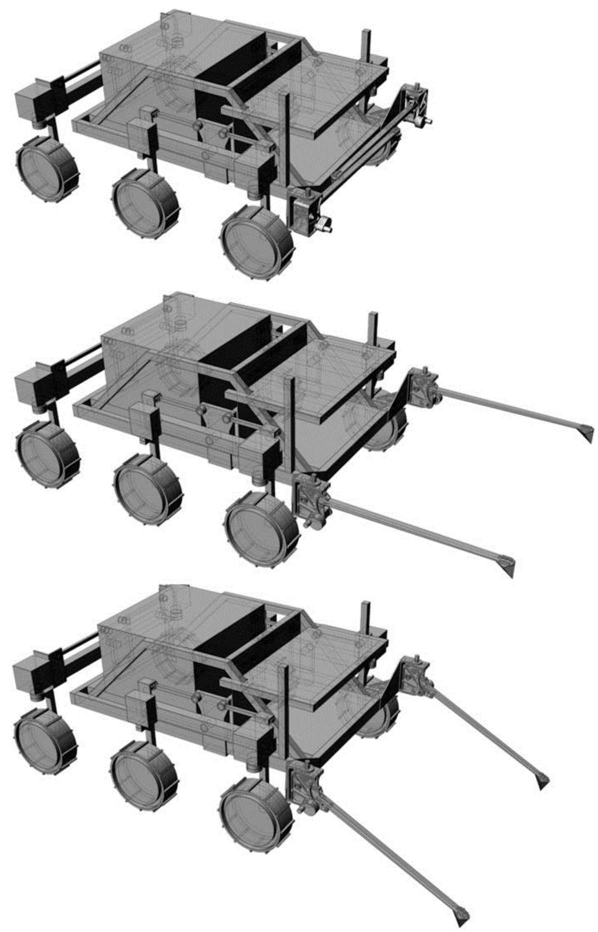

Figure 10. The test rover fitted with the PathBeater soil sensor. Top: PathBeater's arm stowed; centre: arms extended; bottom: arms deployed. (LSG, R. Waclavicek)

Analyses of the operational modes of PathBeater have been made graphically and with a scale model of the test rover over various scaled landscapes. This work has shown that the test rover's chassis attitudes when climbing/descending hills and crossing over obstacles have an influence on PathBeater's operation, which can lead to re-stowing PathBeater's arms in particularly hazardous situations. Measurement of the rover's attitude during motion as well as the rovers speed will be an input to the control software for PathBeater.

The functional prototype makes extensive use of commercial-off-the-shelf components and rapid-prototype (3-D printing) manufacturing techniques. The actual total mass of the PathBeater system is 4.5kg including its micro-controllers and power amplifiers, which will be installed in the payload bay at the front end of the rover.

Testing of PathBeater involves free-fall drop tests of the penetrator using different types of "soil" to determine footprint pressures. These are followed by free-fall drop tests with the penetrator attached to the arm and determination of the spring's characteristics to achieve the desired degree of penetration. The third phase will be a functional test of the complete system using a mobile rig resembling the payload bay area of the test rover to check the performance of the whole system before proceeding to field trials planned for 2014.

4. CONCLUSION

This paper has presented several soil sensor systems that may be employed by future autonomous extra-planetary rovers. These sensor systems have a variety of soil characteristic detection capabilities, and speeds and modes of operation. When used in concert, they will provide overlapping, redundant means of detecting terrain trafficability through soil characterisation. This level of redundancy will provide an added layer of safety for rovers that are required to navigate unexplored terrain.

While the sensor systems illustrated here are being applied to a small scout rover and a larger primary rover, each of the systems is scalable such that any of them could be applied to a variety of rover sizes and designs; either in a cooperative, multi-system manner as we have proposed, or as single sensor systems. Although these systems are being presented as safety assurance tools, they also have the ability to return scientific data, thus furthering our knowledge of novel environments.

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