THE CANADIAN MARS EXPLORATION SCIENCE ROVER PROTOTYPE

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ABSTRACT

The Mars Exploration Science Rover (MESR) program is part of the Exploration Surface Mobility (ESM) activity currently being undertaken by the Canadian Space Agency (CSA). MESR primarily supports autonomous science prospecting and *in situ* geological analysis operations. The chassis and locomotion system has excellent obstacle crossing and continuous steering from low curvatures down to point turns. The power system is path-to-flight based on nanosatellite and microsatellite heritage. The onboard sensor suite provides excellent situational awareness, and enables fully autonomous precision traverses to sites of interest. The MESR is designed to visually learn a path and then repeat the traverse in either direction autonomously. The software architecture supports a Mars-representative command scheme, providing a mission scripting language for use under limited communication windows and bandwidth constraints. Modularity and flexibility have been built into the architecture for future upgradeability.

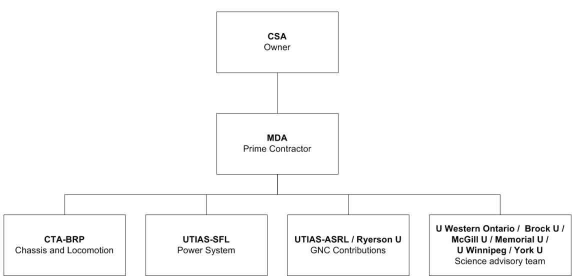

Figure 1: Partners in the MESR program.

1. INTRODUCTION

1.1. Overview

The Mars Exploration Science Rover (MESR) program is part of the broader Exploration Surface Mobility (ESM) activity currently being undertaken by the Canadian Space Agency (CSA). The objective of this program is to develop an end-to-end prototype of a Mars science-class rover system, integrate this system with ESM science instruments and payloads, and perform analogue mission deployments to gain operational experience. MESR leverages and extends Canada's recent advances in exploration robotic systems. Figure 1 shows the organization of government, industry, and academic partners on the program.

The MESR system, shown in Figure 2, primarily supports autonomous science prospecting and *in situ* geological analysis operations. It was designed to provide a rugged mobile testbed for sample collection and analysis instruments (e.g., small manipulator arm, mini-corer, microscope, etc.), with autonomous precision drive capabilities to user-selected sites of scientific interest, with Mars-like communication constraints. The mobility platform, power system, sensor suite, autonomous functions, and command and data handling are presented in Sections 2 through 6, respectively. Future work is described in Section 7.

Figure 2: The Mars Exploration Science Rover at the CSA Analogue Terrain.[Image credit: CSA]

1.2. Related Work

MESR is noteworthy as it is the first time in Canada that so many path-to-flight components have been integrated into a single end-to-end analogue mission system. Among recent planetary rover prototypes, the MESR is most comparable to the NASA JPL's Field Integrated Design and Operation (FIDO) rover, particularly with respect to their intended use for risk reduction through analogue missions in the field [1], although FIDO is more flight-representative. The ESA Exomars Breadboard Rover Chassis, "Bridget" [2], is also being used for field trials [3], but does not have the same level of integrated mission emulation as does MESR.

In addition to field testing specific rover technologies, Canada has also previously performed analogue planetary exploration missions, including geology [4], sample return [5], and *in situ* resource utilization [6]. However, these deployments have not been tightly integrated, meaning that several disparate software and hardware systems must be amalgamated in an *ad hoc* fashion, and many operational steps must be "green carded" (performed by hand). MESR provides the first opportunity for a tightly integrated analogue mission, which is a critical next step for flight readiness.

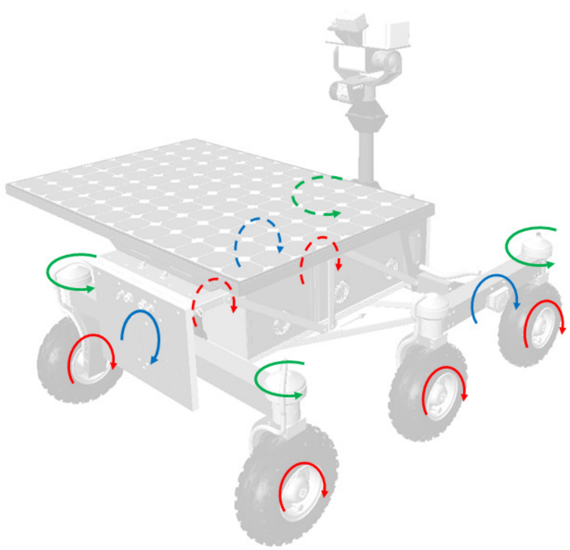

Figure 3: Degrees of freedom of the CLS. Red: traction drives. Green: steering drives. Blue: passive bogie pivots.

2. MOBILITY PLATFORM

2.1. Chassis and Locomotion System

The Chassis and Locomotion System (CLS) was designed and built by Centre de technologies avancées BRP (CTA-BRP), who are world leaders in rugged, off-road terrestrial vehicles. The MESR is a six-wheeled vehicle, with 10 active and 3 passive degrees of freedom, as shown in Figure 3. The chassis configuration is a simple, rigid 3-bogie design, which provides superb obstacle crossing while minimizing mass and mechanical complexity. This suspension arrangement is inherently balanced and does not require a coordination mechanism to maintain the pose of the main body. All six wheels have independent traction drives, and the front and rear wheels have explicit steering. The steering drive limits were chosen to provide continuous steering from straight driving down to point turns.

Table 1 lists the key performance metrics for the CLS, showing excellent ground clearance, obstacle crossing, and gradeability. These features will allow MESR to traverse challenging terrains while on analogue field deployments.

The vision head, avionics bays, and drive components are ingress protected from dust and water, so the rover can withstand light rain or snow without damage. Active temperature controls allow the rover to be deployed in ambient temperatures from -10°C to +40°C, permitting field operations in both arctic summer and desert conditions.

Table 1: Chassis and locomotion system specifications.

Parameter	Specification
Wheelbase	180 cm
Track width	145 cm
Ground clearance	45 cm
Ramp breakover angle	68°
Angle of approach	> 40°
Angle of departure	> 40°
Rollover threshold	36°
Gradeability (terrain)	16°
Gradeability (hard surface)	> 31°
Ground pressure	28 kPa
Maximum speed	12.5 cm/s
Braking distance	< 5 cm
Maximum obstacle	40 cm (slow speed)
Rock hazard	10 cm (all speeds)
Minimum radius of curvature	0 (continuous steering down to point turn)
Payload capacity	70 kg

The front, rear, and top deck of the chassis are payload attachment plates, which provide the threaded mounting holes and weatherproof power and Ethernet connectors which are common across the ESM program (see Figure 4). These plates allow the integrated rover system to be rapidly reconfigured to use the ESM payloads specific to a given analogue mission. To provide a high stiffness-to-mass ratio, the plates are constructed as a honeycomb sandwich panel (HSP), using aluminum for the core, facings, and self-locking helicoil inserts. There are six payload power and data ports, each of which can supply 10 A at 28 VDC. The payload capacity of the rover is 70 kg. With the solar array removed, the fully loaded rover meets all of its performance metrics in Table 1; a small decrease in performance is incurred with both the 70 kg payload and solar array mounted.

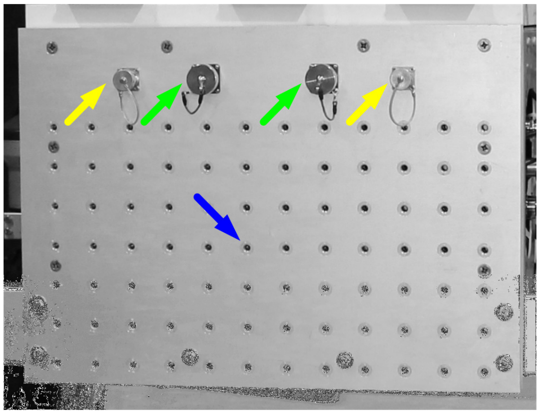

Figure 4: Detail view of the front payload plate. Yellow: 28 VDC power connector. Green: Ethernet connector. Blue: Threaded hole for payload mounting (typical).

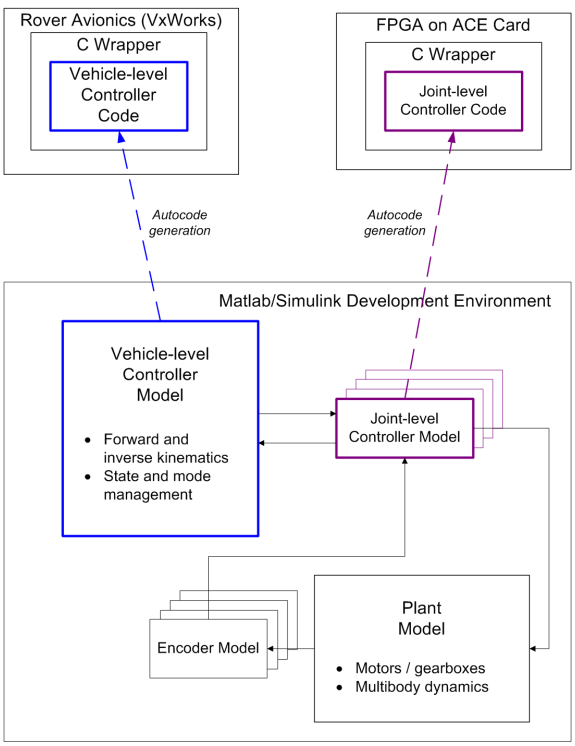

Figure 5: Model-based design approach for the vehicle-level (blue) and joint-level (purple) control systems.

2.2. Control System

MESR uses a distributed control topology. The vehicle-level control, comprising forward and inverse kinematics and state / mode management, runs on a general-purpose CPU. The low-level joint control uses a custom-made Actuator Control Electronics (ACE) card with a Field-Programmable Gate Array (FPGA) to close the joint's control loop, either in velocity (for traction drive) or position (for steering drive). This flight-representative topology and the ACE hardware were developed under the CSA-funded Next Generation Canadarm (NGC) program [7].

The control system was developed using model-based design in Matlab/Simulink, as shown in Figure 5. Both the vehicle-level and joint-level controllers were developed in Simulink and validated using a dynamic model of the rover plant. C language autocode was then generated for both models and wrapped into the rover avionics framework. This paradigm allowed for early controls development and rapid turnaround at each iteration of integration and testing.

The vehicle control system runs on a true real-time operating system, VxWorks. This operating system has an extensive flight heritage, including all of the recent NASA Mars rovers.

3. POWER SYSTEM

The MESR power system was designed by the University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS-SFL), based on their heritage with flight systems for nanosatellites and microsatellites. The power system is capable of producing approximately 320W of generated solar power, and can store approximately 1200Wh using a single 8S6P Lithium Ion battery. The general architecture involves a +28 VDC battery-regulated bus with Peak Power Tracking (PPT) functionality. An overview of the power system specifications is presented in Table 2.

Table 2: Power system specifications.

Parameter	Specification
Power System Topology	Series Peak Power Tracking
Battery	40Ah 8S6P Li-Ion
Solar Panel	320 W
Maximum Output Power	1.3 kW (combined)
Unregulated Output Voltage Range	24V to 32.8V
Power Outputs	24
Communications	CAN Bus

A battery-regulated PPT topology was chosen for several reasons. First, it allows the rover to maximize power generation over a wide temperature range whenever it is needed to power the loads or charge the battery. Second, it decouples the solar array from the power system design; in a PPT architecture, the peak power tracker acts as a solar array-to-bus interface, with each port specified independently. Finally, the battery-regulated architecture has no battery discharge regulator so a low dynamic bus impedance is ensured which is important for the high peak current loads typically seen on a rover.

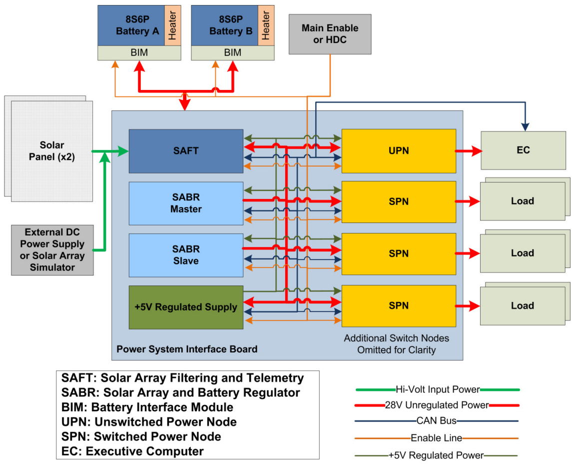

Figure 6: Power system architecture.

Figure 6 presents an overview of the MESR power system architecture. The power system consists of several modular cards arranged on a passive backplane. These cards include:

- Solar Array and Battery Regulators (SABRs)
- Switched Power Nodes (SPNs) with two switches on each node
- +5V regulated power supply
- Solar Array Filtering and Telemetry (SAFT) Module

Two SABR modules provide peak power tracking for the solar array and regulate charging of the battery. A SAFT module filters power from the solar panel and collects telemetry. Twelve SPNs distribute switched power to the various loads in the rover, and can be remotely commanded to individually turn on and off via the Rover Executive software (described further in Section 6). While power is provided from a single battery, the rover supports the ability to carry a second battery for extended range and to hot swap to the spare battery without powering down the rover. A Battery Interface Module (BIM) is attached to the battery and provides this hot swap functionality as well as collecting telemetry from the battery. A regulated +5V power supply provides power to all of the cards in the power module for all digital circuits and Controller Area Network (CAN) communications. An E-Stop Hardware Decoded Command (HDC) is used to instantly disable all SPNs connected to the rover mobility subsystems. Similarly, a discrete master enable signal is used to disable the power system and turn off the rover.

All communications between the power module and executive computer, as well as intra-subsystem communication between power cards is done over a CAN Bus. CAN has excellent error detection capability, support for multiple masters, and provides superior noise immunity. The multi-drop nature of CAN makes it ideal in the event that future system expansion requires distribution of SPNs throughout the rover.

Tests in the CSA Analogue Terrain have shown that a full day's operation (6 hours of continuous function, traversing 760 m over rough terrain), can be performed without depleting the battery or having to swap batteries, which is highly advantageous for field deployment.

4. SENSOR SUITE

MESR supports a full array of navigation and situational awareness sensors, as shown in Figure 7. Commercial off the shelf (COTS) hardware was used to reduce costs. The zoom camera is an 8 Mpixel colour imager with a diagonal field of view between 5° and 75°. It is placed at the centre of rotation of the pan and tilt axes to facilitate generation of panoramic images, and typically supports assessment of science targets and situational awareness. The stereo camera consists of a pair of 50° fixed focal length, colour, 5 Mpixel imagers, on a custom mount with a 30 cm baseline. It is used for navigation and as a potential source of 3D data for science purposes. The lidar is a 270° line scanner with 0.25° resolution and 50 m range, mounted above the pan unit. As the vision head rotates, the lidar sweeps out a full scan of the surrounding terrain. This 3D data is used onboard for terrain assessment and path planning, and at the ground station for science and situational awareness. Finally, three small, wide angle, 1 Mpixel cameras are mounted on the belly of the rover. Each of these cameras images the pair of wheels on each of the three bogies, and provides awareness of the terrain conditions underneath the rover. A viewing analysis was performed by simulating each sensor's location and field of view, and ray tracing to a model of the rover on an ideally flat terrain. Figure 8 shows that the only areas that cannot be viewed by at least one sensor are those immediately outboard of the wheels. The solar array, payload workspaces, and portions of the chassis can also be viewed for monitoring and situational awareness purposes.

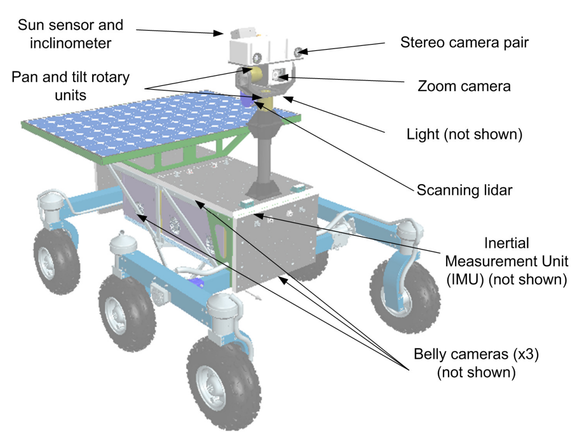

Figure 7: MESR sensor suite.

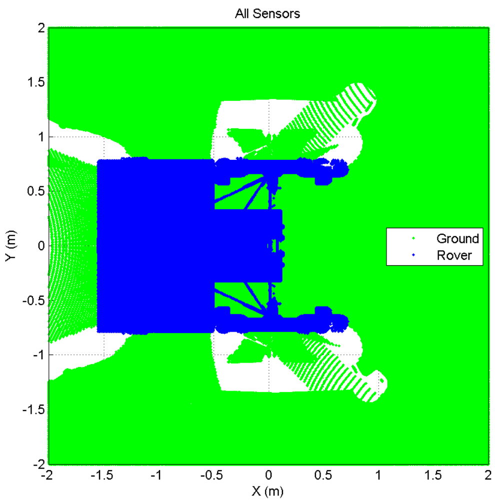

Figure 8: Viewing analysis, showing comprehensive availability of situational awareness data from the MESR sensor suite. Blue: points on the rover body and undercarriage. Green: points on a flat terrain. White: Blind spots just outboard of the wheels.

A navigation-grade inertial measurement unit (IMU) is mounted to the frame of the chassis inside the avionics bay. This sensor is used to perform gravity correction and to reduce heading errors from the wheel odometry. Additional attitude information is provided by the digital sun sensor and inclinometer on the vision head. These feed into the celestial heading estimation function described in the next section. The sun sensor is a space-qualified design with previous flight heritage.

In keeping with the path-to-flight philosophy, MESR does not use any Global Navigation Satellite Systems (GNSS) to localize itself; although such a system could be easily incorporated as a payload if desired.

5. AUTONOMOUS FUNCTIONS

5.1. Component functions

MESR includes a full range of autonomous guidance, navigation, and control (GNC) functions developed by MDA, the UTIAS Autonomous Space Robotics Laboratory (UTIAS-ASRL), and Ryerson University. Each of these components has been thoroughly field tested in planetary analogue environments: Figure 9 shows a testbed rover during field trials in the Mojave Desert (California, USA), and Figure 10 shows the same sensor and GNC suite mounted on the Canadian Breadboard Rover (CBR) during field deployment in the Sonoran Desert (Arizona, USA). Figure 11 shows the ASRL rover driving autonomously in the high Arctic (Devon Island, Canada).

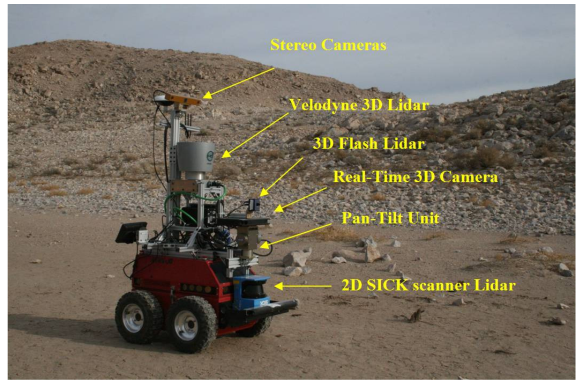

Figure 9: AIRGNC sensor suite and testbed mobility platform in the Mojave Desert.

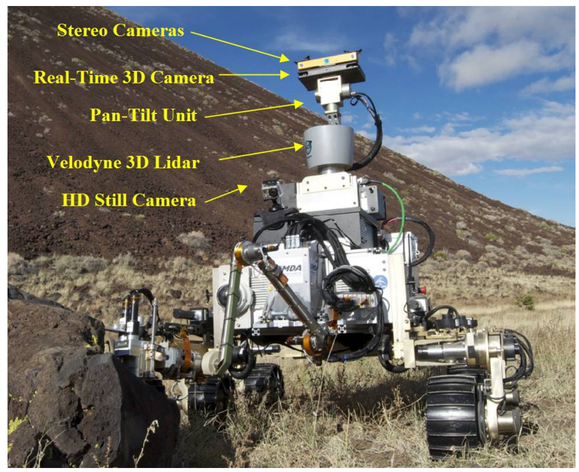

Figure 10: AIRGNC sensor suite on the CBR in the Sonoran Desert.

Figure 11: UTIAS-ASRL field test on Devon Island in the Canadian high Arctic.

The backbone of MESR's autonomy is the Autonomous, Intelligent and Robust GNC (AIRGNC) system. The key functional capabilities of AIRGNC are:

- Terrain assessment: evaluation of slopes, positive and negative hazards, and roughness of the terrain.

- Path planning: finding a safe, traversable path from the current position to the goal location.
- Localization: determining position and attitude with respect to the starting location.
- Path tracking: computing linear and angular rate commands to keep the rover on the planned path.
- Autonomous supervisory control: sequencing and recovery from specific faults.

AIRGNC was successfully field tested in the Mojave Desert on over 7 km of traverse [8], and subsequently deployed for the Canadian Mars Sample Return Technology Demonstration in the Sonoran Desert [5].

Using innovations developed by ASRL, the MESR will be able to perform Visual Teach and Repeat (VT&R). Here, the robot will execute a trajectory, either autonomously or through teleoperation, and build a manifold map of overlapping submaps, each containing the visual features detected by a stereo camera. This collection of feature maps will then be used for localization as the rover repeats the route autonomously. The system has been tested on ASRL field rovers on more than 32 km of traverse, including in a planetary analogue setting in the Canadian high Arctic [9]. Because it enables long-range autonomous behaviour in a single command cycle, VT&R is well-suited to planetary applications, such as Mars sample return.

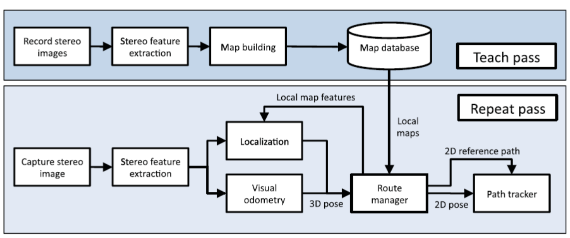

Figure 12: An overview of the major functional blocks of the Visual Teach & Repeat (VT&R) system.

ASRL, in partnership with Ryerson University, has shown that it is possible to use a sun sensor, inclinometer, and clock to determine the rover's absolute heading to within a few degrees [10]. This is an important result, as heading drift is a major source of error in relative localization systems. 10 km of field testing of sun sensor-aided visual odometry on Devon Island have confirmed its usefulness as an online navigation input [11]. Accordingly, MESR uses the ASRL-Ryerson Celestial Heading Estimation (CHE) algorithm as part of its relative localization system, in combination with the AIRGNC IMU-corrected odometry and Visual Motion Estimation (VME) algorithms [8] (see Figure 13).

The integrated GNC software for MESR has been tested on a commercial rover testbed (Clearpath Husky A200); integration testing on the MESR platform is in progress at the time of writing.

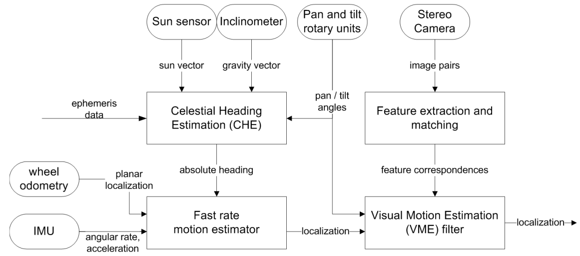

Figure 13: Localization algorithms, which fuse wheel odometry, IMU, sun sensor, inclinometer and stereo camera data.

5.2. Operational Example of Autonomous GNC

A typical operation for the MESR GNC system would be as follows:

- The operator or scientist at the Rover Control Station (RCS) selects one or more long-range goal locations. This selection can use any approach that the operator decides is appropriate, independently of the MESR system; for example, based on a coarse overhead map, or on previous scan data collected by the rover. The goal locations can be selected arbitrarily, without being limited to the rover's on-board atlas map or sensing range. The intent is that these goals can cover a long range traverse (say, on the order of hundreds of metres) while providing some coarse guidance to the rover (say, waypoints on the order of 20 - 50 metres). If no *a priori* map is available, then a straight line connecting the start location to the next long-range goal location will be used as a rough estimate of the path to be followed.
- The appropriate command script containing the selected goal locations is generated, validated, and sent to the Rover Executive. For each goal location (waypoint) in the script:
  - The next goal location is sent to the precision drive command block.
  - The rover takes a high resolution medium range scan of its local environment using the scanning lidar. The previous scan (if it exists) is combined with the current scan to fill in blind spots. The path planner conducts the terrain assessment, and plans a hazard free path toward the goal. (Note that this planning is based on the local high resolution sensor data and does not require any information from a global map.) If the goal is outside of the medium range scan, or if the goal is within the scan but marked as untraversable, the planner will plan a path to the closest traversable point in the scan to the goal.
  - The rover tracks the planned path, using the VME function (if enabled) to localize itself, and its inverse kinematics function to drive the

actuators in the chassis. The rover stops when it reaches the boundary of the medium range map.

- Mapping, terrain assessment, and path planning are autonomously repeated until the current goal location is reached. Contingency plans are automatically executed by the autonomy script; for example, if a path to the next waypoint cannot be reached, the rover may move a small amount and repeat the planning cycle. If the goal location is not reachable, the vehicle will move as close as possible to the defined goal and report its status.
- Telemetry (localization, images, 3D terrain scans) are logged during the traverse, and can be retrieved to the RCS on demand. In particular, the scan data with their corresponding localization estimates are added to the onboard Atlas Map data structure.
- The script may contain commands for acquiring science data at one or more waypoints, at the discretion of the operator.

6. COMMAND AND DATA HANDLING

The software architecture of the MESR system includes several key features to support planetary analogue missions, both in the on-board and off-board software and in the communication protocols which link the two.

The on-board software architecture uses a modular approach, where each key function of both the hardware (e.g., motion control, vision system) and data processing (e.g., path planning, localization, etc.) is self-contained within its own executable Computer Software Configuration Item (CSCI). Each of these modules has an Application Programming Interface (API) which can be invoked remotely, allowing any CSCI residing on any of the processors on the network to access that module's functionality (see Figure 14). The modular approach provides flexibility, in that CSCIs can be easily moved between processors, processors can be added or removed as needed, and modules can be easily upgraded in the future.

The central CSCI in the architecture is the flight-like Rover Executive. This module handles all of the communications with the Rover Control Station (RCS), executes command scripts, and controls the power system so that all of the rover hardware (including the processors themselves) can be power cycled remotely from the RCS. The rich scripting language for the Executive, which is based on Lua [www.lua.org], provides the analogue mission operator with access to all rover and payload functions. Command blocks can be written for commonly executed tasks, such as autonomous precision driving, power cycling, etc.

Communications between the RCS and the rover can be configured in either real-time or Mars-like modes; in the latter mode, the analogue mission planner can schedule communication windows of fixed duration and limited bandwidth, which allows the mission control team to test realistic operational procedures for science planning, script writing, and telemetry gathering. The real-time mode allows the user to teleoperate the rover or to perform technology demonstrations where flight-like communications are not a priority.

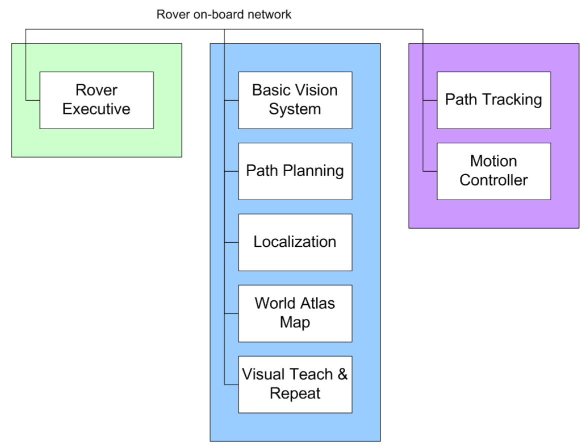

Figure 14: Software modules residing on the three on-board processors.

Telemetry from the various CSCIs has been prioritized, so that the most critical data gets transferred first. The operator can also control the bandwidth of the data stream by selecting low, medium, or high volume telemetry. The communications protocol also supports both reliable and best-efforts messaging, which allows the system to treat time-sensitive or repetitive data differently from regular messages, which improves real-time performance.

The RCS provides a human-machine interface (HMI) for operating the MESR, and can be run from a rugged laptop at the field site, or from a remote "mission control" centre such as the CSA Exploration Development and Operations Centre (ExDOC). There are essentially three classes of interaction with the rover:

- Interactive: The user can teleoperate the rover using a hand controller (typically a game pad), can request data from any of the sensors (e.g., panoramic imagery, lidar scan, etc.), and can call the individual autonomy functions (e.g., perform terrain assessment, plan a path, etc.).
- Scripted: The user can create, edit, verify, and upload scripts and command blocks, as well as manage Mars-like communication windows.
- Engineering: Provides a display of all low-level engineering telemetry from the rover (e.g., temperature readings, motor currents, encoder counts, state/mode information, etc.). Also included are tools for reviewing and plotting past telemetry.

The RCS was designed using Eclipse Rich Client Platform (RCP), which allows the user to reconfigure the size and placement of the various displays, allowing them to customize the HMI to best suit their needs.

Figure 15: MESR climbing into the Jumbo crater at the CSA Analogue Terrain. [Image credit: CSA]

7. FUTURE PLANS

The initial build of the vehicle was completed, and after a brief checkout, the first version of MESR was delivered to the CSA in May 2012. Commissioning of the vehicle is being performed through a test campaign conducted in the Analogue Terrain at the CSA headquarters (as shown in Figure 15), and is ongoing as of the time of writing. Minor hardware modifications and a software upgrade have been planned for a future revision. Once the rover is commissioned, payloads will be integrated. The current planned suite of payloads includes a small manipulator arm, microscope, mini-corer, and a science payload, all concurrently developed under CSA's ESM program.

The integrated exploration system may then be deployed for analogue missions in Mars-like conditions. The objectives of such a mission would include acquisition of scientifically relevant target sample suites (rock, granular material and atmospheric) from various locations from the simulated landing site, and provision of proper context and characterisation information for selected samples. Rover-based scientific instruments would be used to remotely identify and characterize sampling sites and specific samples, and material handling instruments would collect, encapsulate, and transfer samples.

Future work may include additional or upgraded software modules beyond those already planned, integration with other ESM payloads, and further deployment in cooperation with the international space exploration community.

8. ACKNOWLEDGEMENTS

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