

Rover Technology for Open-Path Spectroscopy Surveys

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Abstract

Rover technology is presented for executing mobile surveys using a distributed spectrometer for open-path, in situ remote sensing. A low-cost research rover prototype was created to verify mobile survey algorithms for a specific absorption spectrometer being designed to acquire open-path measurements of biogenic gases on Mars. Distributed instrument components include the rover-mounted spectrometer and a retroreflector. This paper describes the robotics supporting autonomous surveying as implemented and verified on the prototype rover. The rover provides necessary instrument mobility including hazard avoidance and survey trajectory following, and it emulates key robotic functions of the spectrometer including laser pointing and color vision-based retroreflector alignment. Rover design and surveying capabilities were verified through preliminary tests and validated by executing surveys of small areas.

1. Introduction

Task-oriented algorithms that support systematic mobile instrument surveys are needed for planetary surface characterization on science missions and *in situ* resource mapping on exploration missions. Typical objectives of site surveys include sensor coverage of designated areas. Area coverage problems for mobile robotic survey systems commonly employ sensing devices requiring close proximity to or contact with the measured phenomenon (e.g., ground penetrating radar [1], fluorescence imagers [2], microscopic imagers, and instrumented subsurface moles [3]). For those survey systems, the rover must physically cover most, if not all, of the terrain in the survey area.

Here we deal with coverage of terrain using *in situ* remote sensing instruments and focus on rover technology of relevance to site surveying using such

instruments. In particular, the focus is on a distributed open path spectrometer configuration [4]. *In situ* remote sensing instruments can acquire measurements at significant distances away from the measured phenomenon. In contrast to sensing phenomena at distant points, distributed open-path configurations permit 2-D measurement over terrain across a distance. Such remote sensing methods can be excellent complements to local methods, serving as an efficient means to survey wide areas to localize smaller areas at which contact- or proximity-based surveys should be concentrated. Algorithms such as parallel line sweeps are commonly used to solve robotic area coverage problems of the latter type. Full and partial coverage planners have also been proposed for rovers that survey terrain using proximity-based instruments [3]. For our application, circular and spiral surveys are considered to achieve wide-area coverage.

For context, the target instrument and survey task are described. A rover prototype for mobile survey development and emulation of instrument robotic functions is presented. Implementation of capabilities required by the rover for autonomous surveying is further detailed. Preliminary survey exercises to verify the rover design and survey capabilities are discussed followed by future directions and conclusions.

2. Distributed spectrometer instrument

The survey instrument of interest is the Biogenic Gas Absorption Spectrometer (BioGAS), which is a near-infrared diode laser absorption spectrometer being designed to search for and locate near-surface biogenic gases (water vapor, methane, etc) escaping from beneath the Martian surface [4]. The BioGAS system configuration is comprised of subsystems including a rover-mounted open-path spectrometer, an alignment subsystem to point the spectrometer at a retroreflector, and a mobility subsystem to move the instrument spatially over terrain for surveying. A rover carries the

instrument on a pan-tilt unit with tunable diode lasers (each tuned to the absorption frequency of a biogenic gas of interest) and detectors for biogenic gases. The lasers are aimed, in turn, at a stationary retroreflector that reflects laser light back to a detector on the instrument. If one of the gases is absorbed by reflected light impinging upon the detector, the instrument can measure its spectrum, and the presence and concentration of the gas in the atmosphere can be determined [4, 5]. The open path configuration enables detection of gases in the near-surface atmosphere intersected by the laser beam between distributed instrument and retroreflector components. The retroreflector would be rigidly attached atop a post that is either fixed to a lander or emplaced on the terrain and would remain stationary during a survey at a position central to the survey region. A 360° retroreflector (such as those commonly used with theodolite systems by civil engineers for land surveys) is employed so that the rover can acquire measurements from any radial direction where the retroreflector is within line-of-sight. Measurements are coordinated with rover mobility to survey terrain and localize the source(s) of detected biogenic gas. Laser emitter/detector and retroreflector components are spatially distributed by a distance d , allowing an open path (of length $2d$) for the laser beam(s) through the atmosphere (Fig. 1). This laser beam path length is variable as d varies with rover position relative to the stationary retroreflector.

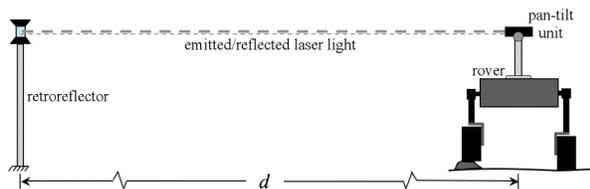


Figure 1. Distributed open-path spectrometer.

Current rover-based *in situ* remote sensing instruments are relatively short sighted and/or utilize point reflectance or thermal emission spectrometers for which each measurement is relevant to a distant spot on the terrain. Effective ranges of several flight and prototype instrument examples are listed in Table 1. These instruments are functionally similar to BioGAS; however, BioGAS would survey sections of the near-surface atmosphere rather than discrete spots on the terrain and would be capable of doing so at maximum effective distances on order of 100s of meters. The longer-range measurement capability coupled with rover mobility enables wide-area surveys of terrain regions. See [4] for further BioGAS details.

Table 1. Rover *in situ* remote sensing ranges.

| Instrument | Effective Range |
|--------------------------|-----------------|
| MER Mini-TES [6] | 10 m* |
| MSL ChemCam [7] | 9 m |
| SEARCH [8] | 10 m |
| Hyperspectral Imager [9] | 20 m |

* To resolve rocks ≥ 50 cm with < 25 cm spatial resolution

3. Mobile spectrometer testbed rover

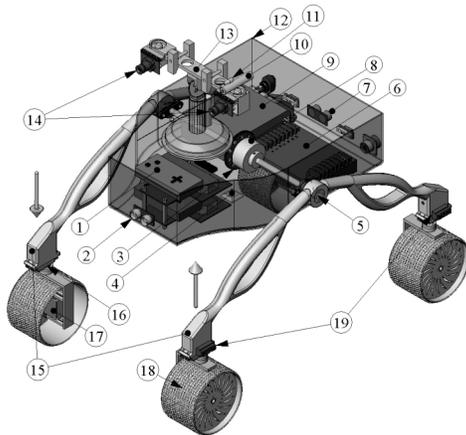
Development of the BioGAS instrument and rover technology supporting its mobility was coordinated but pursued in parallel at different institutions. A testbed was created to facilitate mobility development, in context, without the actual instrument. A simplified platform that supported physical validation of survey algorithms developed in simulation [10], and one that could emulate robotic operations supporting science measurement acquisition was sufficient.

Requirements for the testbed were necessarily high level since the platform would not be the final field platform for the integrated BioGAS instrument system. Adequate support of the mobility and survey algorithm development could be provided by a testbed with the following minimum requirements:

- wheeled mobility system operable in indoor laboratories and on natural/uneven terrain in indoor/outdoor experimental sandboxes;
- chassis supporting a payload comprised of rechargeable power source, embedded computing, and pan-tilt pointing mechanism;
- camera and visible laser (class 3A or safer) on the pan-tilt mechanism, and a separate retroreflector;
- emulated measurement features of the instrument, i.e., laser pointing & reflected laser light detection from up to 3 m (adequate for sandbox tests);
- avionics supporting sensor-based software control for mobility and pan-tilt pointing over a range of motions ($> 270^\circ$ azimuth, $> 90^\circ$ elevation); and
- low cost implementation ($< \$10K$ USD).

These requirements led to the Mobile Spectrometer Testbed Rover (MSTR), a low-cost platform useful for development and preliminary validation of integrated rover and active instrument control ideas. MSTR supports emulation of the BioGAS robotic laser pointing functionality and its retroreflected laser light detection function. It was used to exercise robotic aspects of open-path surveying needed for BioGAS.

MSTR is a four-wheeled robotic vehicle, 61 cm long, 41 cm wide, standing 53 cm high when on a level surface. It has a 26 cm ground clearance, mass of 7 kg and 2 kg payload capacity (beyond essential avionics). The rover with annotated parts is shown in Fig. 2 followed by an overview of its subsystems.



| | | |
|----------------------|-----------------------|------------------|
| 1: XBC controllers | 7: Rear sonar | 14: Cameras |
| 2: Front sonar | 8: Differential pot | 15: Rockers |
| 3: Differential gear | 9: Li-ion battery | 16: Steer motor |
| 4: Tilt sensor | 10/11: Laser/Detector | 17: Drive motor |
| 5: Differential axle | 12: Chassis | 18: Spiked wheel |
| 6: DC-DC converter | 13: Pan-tilt unit | 19: IR rangers |

Figure 2. MSTR configuration.

3.1 Mechanical subsystem

The mobility subsystem consists of an all-wheel drive-and-steer rocker suspension with a passive differential joint connecting 2-wheel rocker assemblies on each side. Spike-treaded 11 cm wheels provide enhanced traction on hard-packed soil/rocks. This configuration enables traversal of rocks up to 1.3 wheel diameters in height. DC motors drive the vehicle while servomotors steer it. DC motors also drive both axes of the pan-tilt mechanism. All mobility motors utilize a full set of titanium gears for added torque and strength (48 times stronger than nylon gears). The stall torque for each rover drive wheel motor is 417 oz-in (3 N-m). Rover maximum speed is 30 cm/s. However, nominal speed for experimentation was limited to 21 cm/s.

The main structural components (chassis, rocker assemblies, wheels) are fabricated of ABS plastic using rapid prototyping methods; the differential axle is aluminum. The dominant hardware expense was a fabrication cost of almost \$5K USD (40% less than an all-aluminum fabrication). The total cost of MSTR fabrication plus key parts was \$7K USD.

3.2. Electrical and computing subsystem

The primary power source is a 15V Lithium-Ion rechargeable battery that delivers 121 Wh of energy to several components via a DC-DC converter. The main components are two XBC robot controllers [11] supporting communications, the sensor suite, and all

motor control. The 15V supply feeds internal battery charging circuits on each XBC controller. The XBC controllers were selected due to their combination of relative low cost and built-in, easy to use facilities for quickly prototyping robotic systems — DC/servo motor control, plug-and-play interfaces for common sensors and a color camera, along with an extensive software library supporting these. The XBC provides built-in closed-loop motor control for the drive-wheel DC motors using backward electro-motive force (back-EMF) voltage as motion feedback. It integrates back-EMF voltages for each drive motor and converts them into motor position updates at 200 Hz; in addition, it provides accurate, smooth PID position control [11]. This is an attractive control solution for motors without built-in encoders. DC motors on the pan-tilt mechanism are also controlled using the built-in back-EMF position sensing and PID controller. The pan/tilt axis is homed using a digital axis-limit switch to initiate relative sensing of pan/tilt angle. Wheel steering motors are controlled by issuing open-loop steering angle set-points to servo controllers built-into each steer motor enclosure. These servo controllers perform closed-loop motor shaft rotation control using potentiometers for absolute angle position feedback.

The main CPU on each XBC is a 32-bit ARM7 processor operating at 16.78 MHz. The maximum serial communication rate for downloading firmware/application software and uploading data is 38.4K baud. Serial communication between two XBCs across a separate TTL serial port can occur at up to 57.6K baud.

3.3 Sensor suite

MSTR has a sensor suite for external rangefinding and internal state supporting the required “instrument” and mobility operation. The pan-tilt mechanism carries optical sensors needed to grossly emulate the open-path absorption spectrometer including a pair of color cameras and an analog light detector. C3088 digital cameras using the OmniVision OV6620 CMOS imaging sensor (356 x 292 array size) are used. A common laser pointer mounted next to the left camera is electronically integrated and controllable via software. The laser pointer can emit a collimated beam for a distance up to 365 m. The light sensor is near-bore-sighted with the laser pointer to detect returned laser light when the laser is pointed at a retroreflector.

Obstacle detection sensors include forward- and rearward-facing sonar modules as well as side-facing infrared (IR) ranging modules on the lower fore and aft segments of the rocker assemblies (see Fig. 2). Proprioceptive sensors supporting mobility include a potentiometer measuring rocker articulation angle and a 2-axis tilt sensor measuring rover body pitch and roll.

4. Rover technology

Several robotic capabilities are needed to enable the wide-area surveying function of an instrument system such as BioGAS. The rover technologies implemented on MSTR include basic mobility, navigation, hazard avoidance, survey trajectory following, and 3-D laser pointing as well as vision-based target recognition and alignment. The implementation is described below.

4.1. Basic mobility and navigation

The kinematic design of the MSTR mobility subsystem provides forward and backward motion as well as double-Ackerman steering permitting turning-in-place and arc turns at radii ≥ 30 cm. The all-wheel steering also permits driving in off-axial directions without changes in rover yaw, i.e., “crabbing.” Crabbing offers more efficient maneuverability over short distances (in the form of single translations in any radial direction) that would otherwise require a series of alternating forward, backward, and turning motions. This is even possible over rocks since the rocker suspension behaves as it would during nominal driving, although with increased susceptibility to unintended yaw. The rocker assemblies articulate with a couple moment about the rocker-chassis joint due to the passive differential axle connecting them on either side. This keeps the chassis fairly level during traversal of uneven terrain. Safeguarded mobility is facilitated when sampling the rocker articulation potentiometer and stopping rover motion if the articulation reaches a preset safety limit on rough terrain. Further safeguards protect against potential vehicle tip-over on slopes or rugged terrain that cause pitch/roll to reach preset safety limits. MSTR tip-over stability limits are 38° pitch and 28° roll.

Due to similarity of the MSTR double-Ackerman steering to that of the MER vehicles, its steering kinematics model was derived from MER models [12]. The XBC provides wheel rotational displacements as back-EMF-derived position data in counter ticks. MSTR’s 0.3 mm/tick drive resolution is the basis for position estimation by wheel odometry from which rover heading is derived via kinematic equations of motion [12], thus allowing point-to-point navigation.

4.2 Hazard avoidance

MSTR employs a reactive sensor-based approach for avoiding isolated obstacles using sonar and IR rangefinders, which continually check for non-traversable geometric hazards within their ranges. When the front sonar detects potential hazards during forward motion, the reactive behavior is to “trace” the

hazard until the rover is able to resume traversal along its original bearing. Such tracing can be executed in clockwise or counter-clockwise directions relative to the original bearing; the algorithm is biased toward the hazard’s retroreflector-facing side. The behavior makes combined use of straight-drive, turn-in-place, and crab motion primitives to perform its task. The 30° span, 2 m range sonar in the front and rear of the rover provides broader coverage for hazard detection in the principal driving directions than the sparse 30 cm point-range coverage by IR on either side. Several areas around the rover perimeter lack sensor coverage (improvement is possible with additional sensors). The current sensor coverage is not conducive to safe, non-lateral crab maneuvers. An effective algorithm for the current sensor suite and coverage uses the sides of the sonar cone and IR to “sense-and-nudge” its way around an obstacle along a piecewise linear path.

4.3 Active instrument pointing and alignment

The camera and laser pointer are configured on the pan-tilt mechanism such that the laser beam hits the retroreflector when it is centered in the camera field of view (FOV). In order to emulate the spectrometer measurements the rover needs to first point its laser in the direction of the retroreflector with accuracy sufficient to place the retroreflector image within the camera FOV. The 3-D location of the retroreflector is fixed and known *a priori* and the onboard navigation system maintains an estimate of the rover pose relative to the retroreflector. Inverse kinematics equations for the pan-tilt mechanism map 3-D target coordinates from rover body frame to pan and tilt angles necessary to aim the laser at a designated target. Given a 3-D world coordinate, the rover pose can be used to transform the point into the rover body coordinate frame. The pan-tilt inverse kinematics can then compute the pan and tilt angles. Whenever the computed pan and tilt angles are within the controllable ranges of motion of the mechanism the rover can aim the laser pointer at a commanded 3-D world coordinate by moving the axes accordingly.

A prototype retroreflector was used which consisted of a cylinder, 13 cm in diameter and 24 cm tall, wrapped with 3M™ Diamond Grade™ DG3 Series 4000 Retro-Reflective Sheeting. Empirical tests revealed that this material reflects incident visible laser light back to its source whenever the angle of incidence is within $90^\circ \pm 40^\circ$ (where 90° corresponds to a perpendicular laser incidence angle). This offers some margin in the accuracy required for MSTR laser pointing. Further margin is available due to the size of the retroreflector. That is, laser light is reflected back toward the detector (at some loss of intensity reaching

the detector) even if pointed off-center of the retroreflector and within the incidence angle range above. The margin is more than sufficient to accurately point at the retroreflector from practical distances in the sandbox test facility.

4.3.1. Retroreflector alignment. Once pointed in the proper direction with the retroreflector in the camera FOV, finer alignment is desired before taking a (emulated) measurement. Color blob detection and tracking features of the XBC vision module are used. This functionality allows calibration of the cameras for sensitivity to a 7 cm-tall color band wrapped around the retroreflector. Calibration consists of pre-assigning color models that are saved to flash memory for use by the XBC color tracking algorithms [11]. The color band serves as a target for color blob detection and tracking (currently using only one of the two cameras).

The alignment algorithm uses the color target position in the camera FOV as feedback to visually servo the pan/tilt motor such that the target becomes centered in the FOV. The algorithm divides the FOV into rectangular quadrants similar to a Cartesian plane with origin at the center of the FOV. When activated by command, the algorithm constantly checks to see if the target is in the FOV. To facilitate centering the target in the FOV, the algorithm considers a sub-frame of 80x130 pixels around the origin. If the color target is detected within the FOV but outside of this sub-frame, appropriate pan/tilt directional motion is made for the quadrant in which the target appears. When the target is detected within the sub-frame the algorithm stops active tracking and maintains the camera gaze.

With the color target centered, finest alignment of the laser pointer with the retroreflector is achieved and an emulated spectral measurement can then be taken. This emulation consists of firing the laser and using the analog light sensor to detect reflected laser light, indicating a completed measurement. Light detector sensitivity is software-adjustable. To further enhance its sensitivity it is baffled for directionality along the expected direction of reflected light.

4.3.2. Retroreflector ranging. Open-path length between the instrument and retroreflector is an important parameter that enables computation of gas concentrations measured by the actual BioGAS instrument. For MSTR, features of the XBC color vision library facilitate retroreflector ranging based on color blob size detection. The actual BioGAS instrument would use a more accurate means to measure range to the retroreflector such as laser ranging (based on time-of-flight or phase difference) or visual methods employing a zoom lens.

XBC libraries include functions to calculate color blob centroid, size, major/minor axis and angle [11]. The calculated blob size of the same color target used for alignment is available as needed. A closed-form relationship between color target blob size in an image and actual target distance from the camera was empirically determined as a close, least-squares fit to a power law. This allowed retroreflector range to be computed in a manner similar to visual looming [13].

4.4 Autonomous surveying

The rover relies on functionality described above to execute survey navigation algorithms. Concentric circular or spiral survey trajectories are compatible with the distributed configuration and measurement task. A designated *survey region* with a stationary retroreflector at its center can be covered by traversing concentric circular trajectories. The location of the retroreflector is known and considered to be the origin of an inertial coordinate system in which the survey region and task is defined. Rover pose during surveys is estimated relative to this coordinate system. Beginning at a designated radial distance from the retroreflector, the rover moves in arc-increments stopping periodically on the trajectory to acquire open-path spectra. We refer to these measurement locations as *m-nodes*. Measurements along a line-of-sight between the rover-mounted laser emitter/detector and the retroreflector account for 2-D coverage of terrain below the line-of-sight. An accumulation of such linear measurements from discrete radial locations and distances achieves survey region coverage. The following four key parameters are used to command a concentric circular trajectory covering a given survey region (Fig. 3): innermost circle radius, ρ_i ; radial distance, δ_c , between circumferences of consecutive circles; arc length, s , between consecutive *m-nodes* on a circle; and positive integer, n , designating the n^{th} or outermost circle encompassing the survey region.

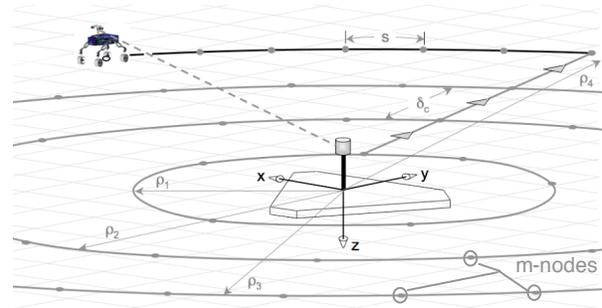


Figure 3. Circular survey and parameters.

The algorithm assumes the rover is within the survey region and the retroreflector is within line-of-sight. If it is not, no measurement is attempted. The survey completes when the n^{th} trajectory is followed. BioGAS surveys would also terminate with a positive gas detection, which MSTR does not yet emulate.

The trajectory following algorithm must be able to guide the rover onto the trajectory from arbitrary poses. This applies when a survey starts and when recovering from maneuvers that cause the rover to deviate from the trajectory. The process involves determining a close, free-space point (x_c, y_c) on the trajectory and navigating to it. This point is at the distance from the rover to the trajectory along the rover-retroreflector direction, θ_r (see Fig. 4). Rover-retroreflector distance, d_r , is measured as described earlier. If the rover is inside a circle of radius ρ that it must drive to, it orients itself along θ_r , and drives outward a distance, $(\rho - d_r)$; if outside, it orients along θ_r and drives $(d_r - \rho)$ inward. The former case is illustrated in Fig. 4.

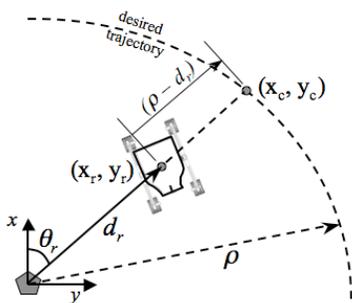


Figure 4. Finding a trajectory from inside.

A spiral survey is traversed in a similar manner, differing only in that the rover drives in arcs along a trajectory of continuously increasing radius and needs no specific maneuvers to transition between successive spiral branches at larger radii. Further details can be found in [10]. Circular and spiral surveys are configured in a flexible manner to achieve desired degrees of resolution and area coverage using the key parameters (ρ, δ, s, n) . The surveys are primarily constrained by rover kinematic limitations, instrument maximum range, and terrain topography in the survey region whether executed radially inward or outward.

4.5. Software implementation

MSTR onboard software was written in Interactive C (IC), a version of the C programming language created for robot controllers and educational computer programming [11]. Software modules available within IC libraries were leveraged for cameras, color tracking, and back-EMF motor control. Software was developed

for primitive functions and motion behaviors needed to support mobile survey tasks. The software architecture executes commands received from a remote operator.

Embedded software is distributed across two XBC controllers. XBC-1 primarily serves as the mobility controller and runs the software for most functionality including the interface to an external base/operator. XBC-1 controls all mobility motors and one camera; it also reads attitude, articulation, and light sensors, plus forward rangefinders. XBC-2 serves as the emulated instrument controller; it runs software to control the pan-tilt mechanism and one camera, reads pan and tilt angle positions, and toggles laser illumination. It also reads rearward rangefinders. XBC-1 serves as host to XBC-2 via physically connected TTL-level serial ports. XBC-1 switches modes between external base communications and communication with XBC-2, as necessary, over the serial link using a custom protocol. XBC-2 software runs in polling mode waiting for “instrument” commands or sensor queries from XBC-1 that it can execute. When XBC-1 sends a valid command, XBC-2 parses and executes it, sends any resulting telemetry to XBC-1, and resumes polling.

5. Testbed verification

Capabilities described above were implemented and tested individually on MSTR and later integrated to exercise surveys in lab and outdoor sandbox test areas. Concentric circular surveys were sequenced for preliminary runs in the lab covering a small (25 m^2) survey region. The 4 key parameters were $(\rho_1, \delta_c, s, n) = (1\text{m}, 1\text{m}, 78.5\text{cm}, 2)$, i.e., a survey of 2 circles beginning 1m and 2m from the retroreflector with 8 and 16 m-nodes, respectively. A snapshot from one of the indoor surveys is shown in Fig. 5 with MSTR on the 2nd circle acquiring a measurement at an m-node. For all surveys, MSTR spent 6 seconds at each m-node to account for emulated measurement time (arbitrarily chosen in lieu of time durations for BioGAS).



Figure 5. MSTR during indoor survey.

Circular surveys were run next in a 6.4m x 23m outdoor sandbox. Survey regions were thus constrained by sandbox dimensions to a 40 m² area allowing circles up to ~6 m in diameter. MSTR executed runs similar to those completed indoors and performed as intended. Fig. 6 shows snapshots of MSTR in the sandbox.



Figure 6. MSTR in outdoor test area.

Experimentation with lateral crabbing drives built confidence in their utility during transitions from one completed circle trajectory to the next. They offer a more efficient maneuver, time- and energy-wise, than the alternative of turning in place, driving to the next circle-start, and turning in place to begin surveying the next circle (as suggested by the algorithm). Lateral crabbing performed reliably in the lab and sandbox.

Each MSTR requirement was verified through individual capability tests and integrated survey runs. The completed surveys of small areas validated the required functionality. Most issues due to the crude emulation of instrument optics were overcome by refined adjustment of hardware/software settings. Color target detection suffered from ambient light interference indoors and outdoors. Reliable alignment performance was achieved by adjusting pixel ranges accepted by the blob tracking color model, a benefit of color pixel filtering and robustness to lighting changes enabled by the XBC [11].

Optical feedback of reflected laser light was tested in varied lighting conditions. Factors influencing performance include variations in ambient lighting, detector sensitivity setting, and the amount of opaque baffling around the detector element. The latter two controllable factors were adjusted for the most reliable indoor and outdoor performance. The light sensor was tested with and without lenses to focus returned laser

light onto its detector element. Simple concave lenses did not yield dramatic improvements for the basic MSTR configuration but lenses are known to improve feedback for BioGAS [4, 5]. In outdoor settings an optical filter can be used to neutralize ambient light thus enhancing the detection of returned laser light.

6. Future directions

Further work is needed to explore limitations of the distributed spectrometer configuration in operational scenarios. For example, certain combinations of rover pose, limited pan-tilt mechanism ranges of motion, and local terrain topography may create conditions under which the rover cannot point at the retroreflector. The MSTR platform is useful for characterizing such geometric limitations in terms of system parameters.

In the near future, surveys will be conducted in the field with the BioGAS instrument integrated on a commercial robot to detect and localize gas sources. In the meantime, MSTR can be used to reveal robotics operational issues and constraints for such surveys, facilitating efficient field operations for BioGAS.

The baseline approach is constrained to single site surveys due to the stationary retroreflector. Relaxing this constraint is a goal of future work to enable rovers to carry a portable retroreflector. Manipulation or mechanism solutions for emplacing or retrieving a retroreflector on or from terrain are needed to enable similar surveys at multiple sites.

The rover and stationary retroreflector configuration is a relatively simple and cost effective means to perform mobile open-path surveys. Configurations of two rovers are also promising. Prior related distributed spectroscopy research considered a two-robot system in which one carried tunable diode lasers and the other carried the spectrometer's detector to perform cooperative remote sensor-based surveys [14]. This configuration is worthy of further consideration toward realizing multiple site science surveys and land surveys for outposts (see Fig. 7). Low-cost MSTR vehicles could be used to explore such configurations.

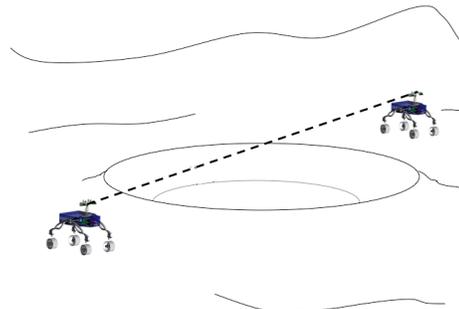


Figure 7. Two-rover distributed spectroscopy.

7. Conclusion

Planetary surface mobility is an invaluable means of transporting *in situ* science instruments from place to place for isolated point measurements. A means to navigate instruments throughout designated regions to acquire remotely sensed measurements comprising spatial surveys is also of value. The distributed, open-path measurement configuration discussed in this paper represents a viable approach to performing wide-area mobile surveys. The MSTR vehicle serves as a testbed for exploring the feasibility of such systems and related surveying algorithms. Functionality required to execute surveys while emulating robotic functions of BioGAS was verified and validated in surveys of small indoor and outdoor areas. While further operational characterization is needed to mature the surveying capabilities for integrated operations with BioGAS, MSTR proved viable for pursuing mobility research supporting its configuration. Its relative low unit cost also makes it an inexpensive option as a research platform for multiple-rover surveying systems.

Instruments employing lasers and retroreflectors have significant space mission heritage, primarily in ranging applications. The BioGAS instrument that this work supports is an example of their use for open-path spectroscopy, a common technique for atmospheric remote sensing. Research described herein augments these technologies with mobility, thus extending their applications to near-surface mobile surveying.

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