Rover Prototype for Mobile Surveying Technology Development

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***Abstract*–** *This paper presents mobile surveying technology associated with use of* in situ *remote sensing instruments with spatially distributed components, and a testbed rover prototype created to facilitate surveying technology development. The system emulates a distributed open-path spectrometer for use with single or multiple rovers to achieve wide-area survey coverage. Rover technologies supporting autonomous surveying or prospecting are described including basic mobility, navigation, hazard avoidance, survey trajectory following, and 3-D optical instrument pointing with associated vision-based target recognition. This technology extends the application of* in situ *remote sensing instruments to wide-area mobile surveying. Portability of distributed immobile instrument components further extends the applicability of the system from single-site to multiple-site surveys.*

Keywords: Rover technology, mobile surveying, open-path spectroscopy, low-cost mobile platform, prospecting.

1 Introduction

On Earth, the exploration and settlement of uncharted territories requires prior prospecting and surveying for useful resources and science data. The same is true for exploration and eventual human settlement of outposts on planet surfaces. Space agencies rely on precursor robotic missions to acquire the data and information necessary to understand planetary surface regions of interest and the feasibility of sending human explorers on future missions. Future precursor missions will require instruments, tools, and supporting robotics to achieve prospecting and surveying tasks. Related functionality will continue to be necessary for later long duration missions and missions of sustained human presence. Surveying refers to the systematic method or technique of making measurements essential for accurately determining the geo-spatial location of commodities of interest in a designated area. Prospecting refers to the methodical and qualitative physical search or exploration for the commodity. In addition to suitable instruments and tools, intelligent robots will need effective techniques for performing these tasks. Mobile robotic vehicles, or rovers, will carry survey systems onboard such as ground penetrating radar, terrain mapping sensors, soil samplers and penetrometers, and various spectrometer types for local and remote sensing. In a manner similar to land surveying by civil engineers, utility rovers will help to characterize landing, exploration, and settlement sites as well as map resources *in situ* [1].

This paper describes robotics technology that will be needed for systematic mobile surveys on future science and exploration missions requiring site characterization, resource mapping, or prospecting. An inexpensive rover prototype useful for research, development, and evaluation of mobile survey approaches using *in situ* remote sensing instruments is presented. Section 2 describes its target application, surveying, and the instrument configuration of interest. The prototype rover is presented in Section 3 followed by descriptions of its key subsystems and onboard technologies for executing autonomous surveys in Section 4. A means to extend the applicability of the instrument configuration to multiple site survey is discussed in Section 5 followed by conclusions and future work in Section 6.

2 Mobile robotic surveying

Robotic surveying is a growing technological trend for civil engineering contractors on Earth. More and more contractors are greatly improving their productivity by adopting robotics technology for surveying associated with tasks such as construction staking for public works projects, tunnels, subdivisions, etc that enable accurate mapping and construction [2]. As a result, more and more human work crews are accompanied by robotics technology and equipment. The robotics employed to date for Earth-based surveying, however, is typically limited to equipment or measurement devices that still require human crew members to perform key functions – the state of the art is, effectively, immobile robotic instruments.

By analogy, preparation of sites away from Earth such as on the lunar surface will require similar tasks but will initially be performed on precursor missions solely by mobile robots, albeit teleoperated at times by humans on Earth. While astronaut crews will continue to use robot partners on later missions to enhance productivity, precursor systems must be more capable than current Earth-based robotic instruments. Mars rover missions to date represent the state of the art for planetary surface robotic capabilities. Mobility/navigation functionality and science instrument platform characteristics of Mars rovers can be combined with robotic surveying technology to produce the utility rovers and approaches needed for precursor missions to planetary surfaces.

2.1 Remote sensing survey instrument

The survey instrument of interest is the Biogenic Gas Absorption Spectrometer (BioGAS), a near-infrared diode laser absorption spectrometer being designed for use on a rover to search for near-surface biogenic gases (water vapor, methane, etc) escaping from the Martian surface [3]. The BioGAS system configuration is comprised of a rover-mounted open-path spectrometer, an alignment subsystem to point the spectrometer laser at a retroreflector, and a mobility subsystem to move the instrument spatially over terrain for survey coverage. A rover carries the instrument on a pan-tilt unit with tunable diode lasers and detectors for each biogenic gas. 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 can be determined [3-5].

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 in 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. BioGAS would survey sections of near-surface atmosphere 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 [3] and [5] for further BioGAS details.

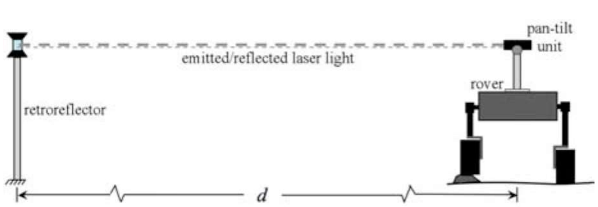
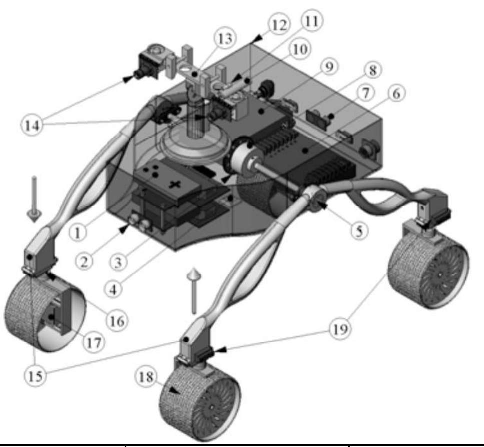


Figure 1. Distributed open-path spectrometer.

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 [6] and one that could emulate robotic operations supporting science measurement acquisition was sufficient. The resulting Mobile Spectrometer Testbed Rover (MSTR), shown in Fig. 2 with annotated parts, 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 dominant MSTR hardware cost was about $5K USD for fabrication. All-aluminum fabrication would cost 40% more. Total cost including key parts (except the pan-tilt unit which is reused from a former project) was $7K USD.



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 Rover hardware subsystems

The main structural components (chassis, rocker assemblies, wheels) are manufactured by rapid prototyping methods using ABS plastic; the through-chassis differential rod is aluminum. Maximum ground speed is 30 cm/s but limited to a 21 cm/s nominal speed for experimentation. A primary 15V Lithium-Ion rechargeable battery delivers 121 Wh to several components via a DC-DC converter that steps the main supply down to required component ratings. The main computing components are two XBC robot controllers [7] supporting communications, the sensor suite, and all motor control. 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 with a resolution of 0.3 mm for MSTR; in addition, it provides accurate, smooth PID position control [7]. 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.

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.

3.2 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 laser 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 (Fig. 3). Proprioceptive sensors supporting mobility include a potentiometer measuring rocker articulation angle and a 2-axis tilt sensor measuring rover body pitch and roll. Rover pose (position and orientation/yaw) is derived from wheel encoder data.

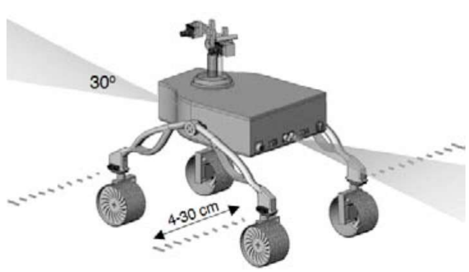


Figure 3. MSTR obstacle detection sensor coverage.

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 summarized below.

4.1 Basic mobility and navigation

The mobility subsystem's kinematic design permits forward and backward motion as well as double-Ackerman (car-like) steering for arc turns at radii ≥ 30 cm and turns-in-place. All-wheel steering also permits driving in any off-axial direction without changes in rover yaw, i.e., "crabbing," which offers more efficient maneuverability over short distances that would otherwise require a series of alternating forward, backward, and turning motions. Monitoring rocker articulation potentiometer readings to ensure they remain within preset safety limits facilitates safeguarded mobility. Further safeguards protect against potential vehicle tip-over on slopes or rugged terrain that cause pitch/roll to reach preset safety limits within stability limits of 38° pitch and 28° roll. Due to similarity of MSTR steering kinematics to that of the NASA Mars Exploration Rovers, its position estimation models were derived from the Mars rover models [8]. As mentioned earlier, wheel rotational displacements are available from the XBC controller and form the basis for rover position estimation by wheel odometry. Rover yaw or heading is also derived from wheel odometry via the kinematic equations of motion [8]. Thus, point-to-point navigation is possible.

4.2 Obstacle avoidance

MSTR employs a reactive sensor-based approach for avoiding isolated obstacles in its path using sonar and IR rangefinders. The sensors continually check for obstacles within their sensitive ranges. When the front sonar detects potential hazards during forward motion, the objective of the reactive avoidance behavior is to "trace" the obstacle boundary until the rover is able to resume traversal along its original bearing. The 30° sonar span in the front and rear of the rover provides broader coverage for hazard detection in the principal driving directions than the sparse IR coverage on either side. Apparent in Fig. 3 are several sensor coverage gaps around the rover perimeter. The current sensor coverage is thus not conducive to safe, non-lateral crab maneuvers, but lateral crabbing is used when IR range to obstacles is close. As an effective algorithm for the current sensor suite and coverage, the rover uses the edge of the sonar cone to sense-and-nudge its way around an obstacle along a piecewise linear path (similar to use of a walking stick by the visually impaired). The algorithm executes obstacle tracing in clockwise or counter-clockwise directions relative to the original rover bearing and with a bias toward the retroreflector-facing side of the obstacle.

4.3 Instrument emulation

Emulating the open-path spectrometer measurement consists of using the pan-tilt mechanism to point the laser at the passive retroreflector from a distance, sensing retroreflected laser light, and measuring range to the retroreflector. The camera and laser are configured such that the laser beam hits the retroreflector centered in the camera field of view (FOV). The rover must first point its laser in the direction of the retroreflector with accuracy sufficient to place the retroreflector image within the camera FOV. This is possible since the 3-D location of the retroreflector is fixed and known *a priori* and the onboard navigation system maintains an estimate of rover pose relative to the retroreflector. Given a 3-D world coordinate $(X, Y, Z)_W$, the current rover pose is used to transform the point into the rover body coordinate frame $(x, y, z)_R$. The following inverse kinematics equations map 3-D target coordinates expressed in rover body frame to pan and tilt angles in the pointing frame (R and P-T, in Fig. 4):

$$\theta = \tan^{-1}\left(\frac{y-O_y}{x-O_x}\right) \tag{1}$$

$$\phi = \sin^{-1}\left(\frac{h}{d}\right) - \tan\left(\frac{O_z - z}{\sqrt{(y-O_y)^2 + (x-O_x)^2}}\right) \tag{2}$$

$$d = \sqrt{(x-O_x)^2 + (y-O_y)^2 + (z-O_z)^2} \tag{3}$$

where (x, y, z) are coordinates of the point being aimed at (typically the retroreflector), O_x, O_y, O_z, are the offsets of the P-T frame from the R frame as depicted in Fig. 4, h is the vertical offset of the laser pointer from the P-T frame, and θ and ϕ are the desired pan and tilt angles, respectively. Equations (1-3) compute the pan and tilt angles that aim the laser at designated targets provided the computed angles are within controllable ranges of motion of the mechanism.

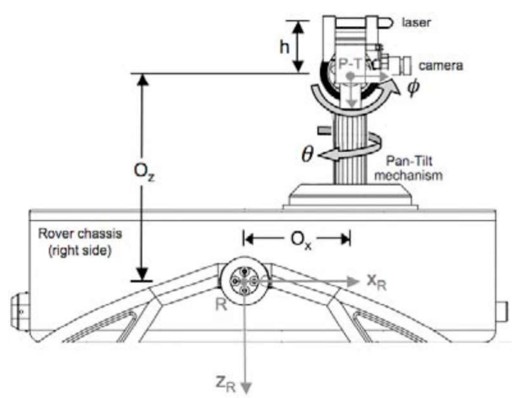


Figure 4. Pointing kinematics.

A prototype retroreflector consisting of a 13 cm diameter, 24 cm tall cylinder wrapped with 3M™ Diamond Grade™ DG3 Series 4000 Retro-Reflective Sheeting was used. Empirical tests revealed that this material reflects visible laser light back to its source whenever the angle of incidence is within 90°±40° (90° ⇒ ⊥). This offers margin in required laser pointing accuracy sufficient to point at the retroreflector from practical distances. Once pointed, finer alignment is desired before taking emulated measurements. A 7 cm-tall color band was wrapped around the retroreflector to facilitate this using the color blob detection and tracking features of the XBC. The alignment algorithm finely visually servos the pan/tilt motors until the color target is centered in the FOV; it then stops active tracking and maintains the camera gaze. With finest alignment achieved, an emulated spectral measurement can be taken consisting of firing the laser and using the light sensor to detect the reflection, indicating a completed measurement. Light detector sensitivity is software-adjustable and further enhanced with baffling for directionality.

The BioGAS instrument requires knowledge of open-path length to compute concentrations of measured gases [5]. While the actual instrument uses laser ranging and a zoom lens to measure range to the retroreflector, MSTR uses color vision to facilitate ranging based on color target size detection in images. The XBC provides functions that calculate color blob centroid, size, major/minor axis and angle [7]. As such, the calculated blob size of the color target used for alignment is available. A relationship between color target blob size in an image and actual target distance from the camera was empirically determined revealing a close, least-squares fit to a power law. This afforded a closed-form expression of retroreflector distance as a function of color target blob size that is used to compute range from the rover's camera to the retroreflector in a manner similar to visual looming [9]. For the current configuration and empirical data for blob size vs. distance, Eq. (4) is the closed-form expression for retroreflector range, d, where B is blob size in image pixels. Ideally, the ranges expressed by Eqs. (3) and (4) should be equal.

$$d = 57.316 \times B^{-0.533} \tag{4}$$

As a byproduct to supporting science measurements, this range measurement facilitates localization updates to rover position. Knowledge of retroreflector distance, position, pan and tilt angles, and rover inertial orientation suffices to update rover position estimates when wheel odometry errors accumulate during surveys. This is illustrated in Fig. 5 where rover position in an inertial frame of reference, W, is given by $\vec{P} = \vec{O} + \vec{d} - \vec{C}$.

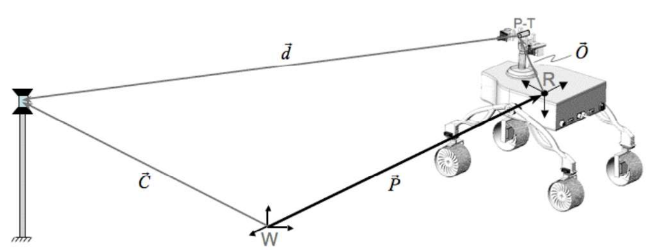


Figure 5. Rover localization geometry.

4.4 Autonomous surveying

Functionality described above enables autonomous execution of survey navigation algorithms. A designated *survey region* with a retroreflector at its center can be covered by traversing concentric circular or spiral survey trajectories [10]. 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 (see Fig. 6). 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 at measurement locations (*m-nodes*) on the trajectory to acquire open-path spectra. An accumulation of measurements between the instrument and retroreflector from discrete radial locations and distances achieves survey region coverage. For BioGAS, a positive detection of gas in the measured spectrum followed by localization of its source, if possible, would terminate the search.

Four parameters are used to command a concentric circular trajectory covering a given survey region (Fig. 6): innermost circle radius, ρ_1; 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 including the survey region. A variation of the same parameters permits commanding of spiral surveys as well. 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. See [10] for further details on the surveying algorithms.

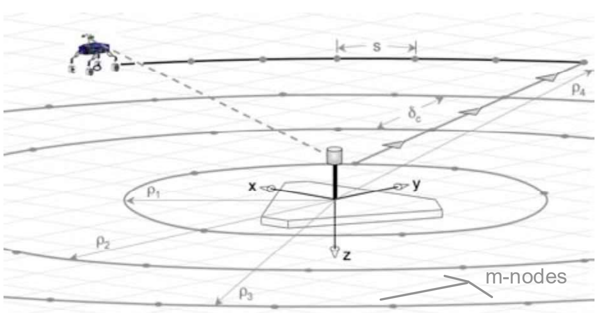


Figure 6. Circular survey and parameters.

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 [7]. 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. Its architecture is broken down into components, with surveying at the highest level, depicted in Fig. 7 and designed to execute command sequences received from a remote operator.

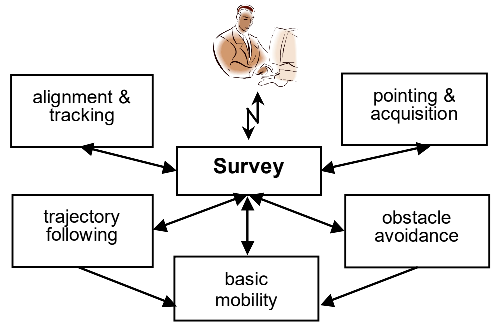


Figure 7. MSTR software architecture.

The embedded software is distributed across the two XBC controllers. XBC-1 serves primarily as the mobility controller and executes most rover functionality including interfacing to the external operator base station. XBC-1 controls all mobility motors and one camera; it also reads attitude, articulation, light sensors, and front obstacle rangefinders. XBC-2 serves as the emulated instrument controller; it controls the pan-tilt mechanism and one camera, reads pan and tilt angle positions, toggles laser pointer illumination, and reads rear rangefinders. The XBCs are physically connected via respective TTL-level serial ports using a custom protocol with XBC-1 serving as host and switching between external communication and communication with XBC-2 as necessary. XBC-2 software runs in polling mode waiting for "instrument" commands or sensor queries from XBC-1 that it can execute. When XBC-2 receives a valid command/sequence it parses and executes it, sends any resulting telemetry to XBC-1, and resumes polling.

5 Enabling multiple-site surveys

Capabilities described above were implemented and successfully tested on MSTR via surveys in lab and outdoor sandbox test areas [11]. The baseline approach is constrained to single-site surveys due to the stationary retroreflector. If the rover could carry and emplace a retroreflector at sites visited along long traverses then the same open-path surveys discussed above could be carried out at each site of interest to mission operators. Various solutions for emplacing and retrieving a *portable* retroreflector on and from terrain are possible that would enable open-path surveys at multiple sites. Preferred solutions would be lightweight and compact (primarily for rover portability). Passively actuated designs would be additionally attractive.

One feasible portable retroreflector concept is described here that could be deployed and retrieved by a robotic arm if integrated onto the MSTR chassis. It would employ a compact assembly consisting of a retroreflector and base connected by an extensible-retractable mechanism serving as a vertical rod when extended. Initially in a retracted configuration, a robotic arm would place the assembly onto approximately level terrain. With the bulk of the assembly's mass concentrated in its base it would sit in a stable posture without additional supports. Once placed onto terrain, the rod can raise the attached retroreflector from the retracted position to a designated height, which becomes a new known location of the retroreflector for subsequent surveys. After surveying at the current site is completed, the rover must return to within close proximity of the portable retroreflector and the rod must be lowered to its retracted position. A retrieval procedure then requires the rover to approach, retrieve, and stow the portable retroreflector onto the rover body for later use. Actuation of the rod extension and later retraction could be done via a radio-controlled motor cued by signals from the rover. Alternatively, to avoid the need for the portable retroreflector to have its own power source it could receive power via an electrical interface engaged by a secure contact on the robotic arm's end-effector. This design concept warrants further study. Its feasibility is supported in part by the fact that the envisioned mechanism is fairly well understood; in fact, the "pop-up" camera mast on the Mars Pathfinder lander [12] and the Mars Phoenix lander is one representative example of an extensible, although one-time deployable, boom. Another feasible solution could be based on the common scissor lift mechanism.

The single rover and retroreflector (stationary or portable) configuration is a relatively simple and cost effective means to perform mobile open-path surveys, and indeed may be all that is required for a given mission. Configurations of two rovers are also promising when multiple rovers are available at a surface site (see Fig. 8). 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 sensing [13].

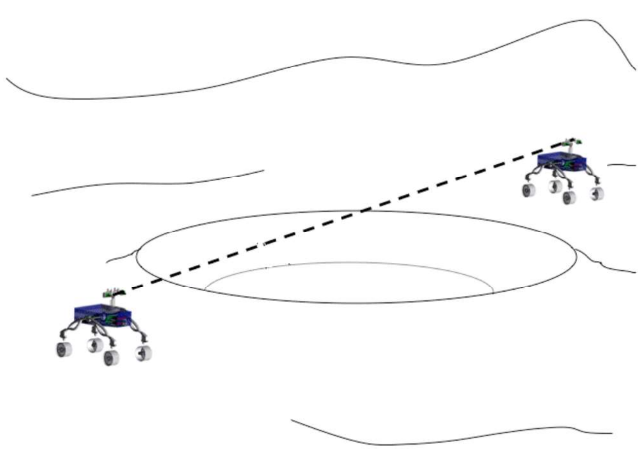


Figure 8. Two-rover distributed spectroscopy.

This configuration is worthy of consideration toward realizing multiple-site science surveys and land surveys for outpost or precursor missions. Low-cost MSTR vehicles could be used to explore such configurations, and relevant performance metrics to evaluate them could be applied accounting for task-specific attributes such as survey and instrument types, area coverage and accuracy, work efficiency, and number of robots [14].

6 Conclusion and Future Work

Planetary surface mobility is an invaluable means of transporting *in situ* instruments from place to place for isolated measurements. Also of value is a means to navigate instruments throughout designated regions to acquire remotely sensed measurements comprising spatial surveys. Distributed and open-path measurement configurations such as discussed in this paper represent viable approaches to performing wide-area mobile surveys. The MSTR vehicle serves as a testbed for exploring the feasibility of such systems, related surveying algorithms, and operations approaches. 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 long-distance ranging applications. They have been successfully used on past space missions and continue to be proposed to date. The Apollo Lunar Ranging Experiment, which produced our most accurate knowledge of Earth-Moon distance based on laser telemetry technology invented by Hildreth "Hal" Walker Jr., still operates today. In the early 1970's the Russian Lunokhod 2 rover was ranged from Earth in a similar manner. More recently, laser retroreflector arrays were considered for the NASA Phoenix Scout lander to enable its localization from Mars orbit. This work augments such technology with mobility, extending its application domain to *in situ* science and exploration tasks for surface and near-surface missions involving mobile assets like rovers and aerobots/balloons.

Further work is needed to explore limitations of the distributed open-path configuration in operational scenarios and to reveal robotics operational issues and constraints for survey and prospecting tasks, facilitating development of efficient field operations approaches for future missions. 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.

Acknowledgments

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