Instrumentation and application of unmanned ground vehicles for magnetic surveying

By

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Abstract

With the recent proliferation of unmanned aerial vehicles (UAV) for geophysical surveying a novel opportunity exists to develop unmanned ground vehicles (UGV) in parallel. This research presents a pilot study to integrate two UGVs, the Kapvik planetary micro-rover and a Husky A200 robotic development platform, with a GSMP 35U magnetometer that has recently been developed for the UAV market. Magnetic noise levels generated by the UGVs in laboratory and field conditions are estimated using the fourth difference method and, at a magnetometer-UGV separation distance of 121 cm, the Kapvik micro-rover was found to generate a noise envelope ± 0.04 nT whereas the noisier Husky UGV generated an envelope of ± 3.94 nT. The UGVs were assessed over a series of successful robotic mapping missions which demonstrated their capability for magnetic mapping, and their productivity and versatility in field conditions.

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Chapter 1

Introduction

1.1 UGVs in Geophysics

Unmanned ground vehicles (UGV) are employed in niche applications to expand the range of ground-based scientific systems into regions which would be inaccessible to standard human operations. Under remote or autonomous operation a UGV can be employed to operate geophysical sensors within difficult environments such as mine tailings deposits (Olmedo & Lipsett, 2016), unexploded ordnance sites (Khamis, 2013; Grusy, 2009), or distant planetary surfaces (Ness, 1979; Grotzinger et al., 2012).

The magnetic method is a widely-used geophysical surveying technique used to map broad geological trends, detect ore bodies, or locate discrete magnetic sources. To resolve these targets magnetometers are deployed by ground crews, mounted on manned aircraft, towed behind ships at sea, and integrated with unmanned aerial vehicles (UAV). On Earth, total field magnetometers are used to detect the amplitude of magnetic fields acting upon a magnetic sensor at a given position. The total magnetic intensity (TMI) is the vector sum of all magnetic components upon the sensor including the induced geomagnetic field generated by the interaction of Earth's solid and liquid nickel-iron core, diurnal fields due to the Earth's interaction with solar magnetic effects, remnant magnetic fields from ferromagnetic materials, active magnetic fields generated from cultural sources such as electrical coils and mobile sources of metal, and passive

magnetic sources which interact with the induced geomagnetic field to produce a magnetic response.

Recently, a new generation of light-weight magnetometers have become available for application in the UAV market which present novel opportunities for integration with unmanned ground vehicles (UGV). Magnetic surveying with UGVs shares many common challenges with UAV applications. A key issue which impacts magnetic surveys performed using UGV-mounted magnetometers is the interference generated by the robotic platform on the magnetic data. Magnetically active and passive components intrinsic to the robotic systems generate a magnetic signature as the UGV travels (Versteeg et al., 2007). A magnetically clean UGV which generates negligible magnetic interference is desired for magnetic exploration to maximize the response of the signal from magnetic targets (Lillis et al., 2011).

An expanded magnetic sensing capability applied to planetary UGV missions extends the investigative range of a UGV beyond the surface and into the near-surface and at greater depth. Figure 1 displays a magnetic map of the Martian surface derived from orbital data (at a nominal 400km altitude) which identifies magnetic striping in the southern hemisphere representing a magnetic target of interest on Mars (Connerney et al., 2005). Application of UGVs for magnetic mapping of planetary surfaces serves to increase the ability to generate high spatial resolution magnetic data over targets of interest which have been identified from surveys at increased altitude.

Figure 1: Global map of Mars crustal remnant magnetization. Magnetic map derived from orbital survey data acquired at a nominal 400km altitude. Image source: NASA Goddard/JPL.

1.2 Objectives

This research project was a pilot study to instrument UGVs with a newly developed GSMP 35U potassium vapour magnetometer developed for UAV geophysical exploration. Two UGV systems were investigated during the course of this research; the Kapvik planetary micro-rover and a Husky A200 robotic development platform. The research outlined in this thesis sought to:

1. Integrate a potassium vapour magnetometer onto a UGV platform with a practical configuration;
2. Determine baseline magnetic signature and noise responses from integrated UGV configurations;
3. Conduct instrumented robotic surveys to evaluate the capability for magnetic mapping.

This research is a contribution towards the development of integrated systems for (semi-) autonomous geophysical exploration applications.

1.3 Structure of thesis

This document is a thesis consisting of two journal-style articles either prepared for submission to, or already published in a peer-reviewed scientific journal on the topic of instrumenting UGVs with a potassium magnetometer for magnetic surveying.

Chapter 1: this chapter presents a literature review of current applications of the magnetic method and UGV systems, and lists the overall objectives of the research

project described in the thesis. A detailed literature review is presented at the start of the articles following in chapters 2 & 3.

Chapter 2: this chapter is a reproduction in whole of a peer-reviewed article published in the July 2017 issue of the International Journal of Astrobiology;

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This article describes the integration of the Kapvik planetary micro-rover with a boom-mounted potassium vapour magnetometer, details the magnetic signature generated by the UGV, and presents results from a case study of a magnetic field survey over a cultural target on Carleton University campus. Table numbers, figure numbers, and formatting have been standardized and updated to be consistent within the thesis. References cited have been included within the references list of this thesis.

Chapter 3: this chapter is presented as journal-style article which describes the integration of a Husky A200 robotic development platform with a tower-mounted potassium vapour magnetometer and details the magnetic signature generated by the UGV. Two case studies are also presented featuring an urban magnetic field survey over the cultural target described in Chapter 2, and a field survey conducted in the rural environment of Hay Bay, south of Napanee, Ontario which contrasts human operated and UGV operated magnetic field surveys.

Chapter 4: this concluding chapter summarizes the results related to the two UGV systems investigated, discusses the comparative strengths of each system, and describes the potential for future research with the integrated systems.

Robotic magnetic mapping with the Kapvik planetary micro-rover

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2.1 Abstract

Geomagnetic data gathering by micro-rovers is gaining momentum both for future planetary exploration missions and for terrestrial applications in extreme environments. This paper presents research into the integration of a planetary micro-rover with a potassium total-field magnetometer. The 40 kg Kapvik micro-rover is an ideal platform due to an aluminum construction and a rocker-bogie mobility system which provides good maneuverability and terrainability. A light-weight GSMP 35U magnetometer, comprised of a 0.65 kg sensor and 0.63 kg electronics module, was mounted to the chassis via a custom 1.21 m composite boom. The boom dimensions were optimized to be an effective compromise between noise mitigation and mechanical practicality. An analysis using the fourth difference method was performed estimating the magnetic noise envelope at ± 0.03 nT at 10Hz sampling frequency from the integrated systems during robotic operations. A robotic magnetic survey captured the total magnetic intensity along 3 parallel 40 m long lines and a perpendicular 15 m long tie line over the course of 3.75 hours. The total magnetic intensity data was

corrected for diurnal variations, levelled by linear interpolation of tie-line intersection points, corrected for a regional gradient, and then interpolated using Delaunay triangulation to lead a residual magnetic intensity map. This map exhibited an anomalous linear feature corresponding to a magnetic dipole 650 nT in amplitude. This feature coincides with a storm sewer buried approximately 2 m in the subsurface. This work provides benchmark methodologies and data to guide future integration of magnetometers on board planetary micro-rovers.

2.2. Introduction

In the context of an astrobiology mission, the use of a micro-rover instrumented with a magnetometer would serve to develop an understanding of the magnetic environment of a planetary surface (Weiss et al., 2014). Mobile measurements of the ambient magnetic field at the surface can be used to delineate regions of remnant magnetization (Lorenz et al., 2003), identify the host rock and/or mineral carrier generating the magnetic field (Lillis et al., 2011), and assess the hazard related to highly energized cosmic or solar radiation (Dartnell et al., 2007). At “regional” scale, the micro-rover would detect changes in magnetic signature (e.g. short or long variations in magnetic intensity, and patterns such as lineaments or circular anomalies). This information can serve to infer boundaries between geological domains and/or changes in regolith composition. Complex missions could involve several “scout” micro-rovers instrumented with magnetometers performing geophysical mapping ahead of a larger

and more sophisticated main rover. Magnetic maps compiled from data acquired by the micro-rovers would guide the trajectory of the main rover. At “local” scale, detailed magnetic mapping can identify magnetic targets of scientific interest, locate subsurface geological features which may host signs of extremophile development, and help to inform the precise locations where to perform astrobiological tests. Examples include the detection of small faults which might be pathways for gas seepage to the surface (methane being of particular interest) (Boivin et al., 2013; Qadi et al., 2015), the delineation of feeder systems of hot springs which are hosts to extremophiles (Samson et al., 2017), and the tracking of lava tubes in the subsurface (Meglich et al., 2003).

The magnetic method is a widely used terrestrial geophysical technique used to map geological trends and detect anomalous magnetic bodies in the subsurface. Figure 2 shows the magnetic anomaly created by a manhole cover at the surface (ferromagnetic material, 1 m diameter) measured by the magnetometer onboard the Kapvik micro-rover at a distance of 2 m. The robotic systems of a micro-rover may also generate a magnetic response (noise) which can obscure the magnetic signal detected. A magnetically clean micro-rover which generates negligible magnetic interference is desired for planetary exploration to maximize the response of the remnant magnetic signal (Lillis et al., 2011).

Figure 2: TMI illustration (vertical plane) of an anomalous response generated by a micro-rover traverse passing within 2 m of a ferromagnetic source. The micro-rover path in plan view is displayed (bottom) as a dashed arrow and star, with the position of a 1 m diameter manhole cover marked by a striped circle.

Magnetic measurements were first collected on another planetary body by the Apollo mission astronauts who deployed stationary (Apollo 12, 15, 16), and portable (Apollo 14, 16) fluxgate magnetometers to record magnetic data on the lunar surface (Dyal & Gordon, 1973). The first robotic magnetometer deployment followed in 1973, when the Lunokhod 2, a lunar rover, included a fluxgate magnetometer mounted on a

long boom at the front of its chassis (Ness, 1979). Although data quality was limited by the influence of ferromagnetic components within the rover, these pioneering efforts generated datasets which were analyzed to detect and characterize magnetic variations within the lunar subsurface (Dolginov et al., 1976). The Apollo 16 magnetic data proved useful in identifying anisotropic magnetic variations within the Lunokhod 2 dataset which enabled modeling the composition and thickness of anomalous subsurface features at depths extending to 300 km beneath the lunar surface (Vanyan et al., 1979). The future Mars InSight mission by NASA-JPL features a geophysical lander equipped with a stationary fluxgate magnetometer, and is currently approved for launch in 2018 (Banerdt et al., 2013). The data acquired by this magnetometer will be used to assess the level of remnant magnetization at the landing site, and to monitor fluctuations in the ambient magnetic field strength and orientation at the Martian surface.

The research project described in this paper was a pilot study to use the Kapvik micro-rover in a new type of mission: robotic mapping of the near subsurface using the magnetic geophysical method. The objectives of the project were to determine a practical rover-magnetometer configuration, measure the impact of rover operations on sensor data quality, and evaluate the capability of the Kapvik micro-rover to perform a robotic magnetic survey.

A robotic survey was mobilized in August 2015 on the campus of Carleton University, Ottawa, Canada, to map a 40 m x 15 m flat field adjacent to the Rideau rapids for magnetic anomalies. During the survey, the Kapvik planetary exploration micro-rover (Setterfield & Ellery, 2013), instrumented with a potassium vapour

magnetometer, was tele-operated within line of sight of the Kapvik base station over a predetermined grid. This paper presents total magnetic intensity (TMI) data gathered during the survey and the interpolation of local field strengths to outline magnetic anomalies for further interpretation of subsurface features.

2.3 Instrumentation and Hardware

2.3.1 Magnetometers

For the purposes of this study, a recently developed GSMP 35U potassium vapour magnetometer (Hrvoic & Hollyer, 2015) was selected for integration with the Kapvik micro-rover. The design of this magnetometer has been customized for use on uninhabited aerial vehicles (UAV) which require a rapid sampling rate, high sensitivity, reduced dimensions, and a low mass budget (Table 1). These parameters are also favourable for the magnetic evaluation of micro-rover interference in terrestrial applications. The potassium vapour magnetometer measures the amplitude of the total magnetic field B as a scalar value.

Table 1: GSMP 35U potassium magnetometer specifications.

Parameter	GSMP 35U
Sensor Mass	0.65 kg
Electronic Box Mass	0.63 kg
Sensor Dimension	158 mm x 64 mm
Electronic Box Dimensions	237 mm x 56 mm x 39 mm
Sensitivity	0.0003 nT @ 1Hz
Resolution	0.0001 nT
Absolute Accuracy	+/- 0.05 nT
Dynamic Range	15,000 to 120,000 nT
Gradient Tolerance	50,000 nT/m
Sampling Frequency	10 Hz
Power Requirements (Sensor warm-up)	50 W
Power Consumption (Operation @ 20C)	14W

To correct for diurnal variations and provide a magnetic baseline a Narod S-100 ring-core fluxgate magnetometer (Trigg & Olson, 1990; Coles, 1988) was employed from an 11.5 km remote location in a magnetically quiet area. Magnetic baseline data was

obtained at a 1 Hz sampling frequency which is sufficient to evaluate the diurnal variations generated by interaction of Earth's geomagnetic field with the sun.

2.3.2 Kapvik Micro-Rover

The Kapvik micro-rover is an all-terrain modular multi-mission prototype designed for planetary exploration and scientific sample acquisition whose development was sponsored by the Canadian Space Agency. Kapvik is composed of a mobile rocker-bogie platform (Setterfield & Ellery, 2013), robotic mast (Liu et al., 2015), and an array of scientific and navigational sensors. Kapvik's complement of sensors and equipment enables completion of a range of mission activities including: colour stereo vision imaging, digital elevation mapping, ultraviolet and infrared terrain examination, sample collection, and measurement of mechanical soil properties. Missions are operated remotely or through a tethered configuration from Kapvik's base station which consists of a radio transmitter, network infrastructure, and laptops which handle control of the micro-rover and monitor its operational status.

Table 2: Instrumented Kapvik micro-rover specifications.

Parameter	Value
Mass: Magnetometer Module	3.18 kg
Mass: Composite Boom	0.45 kg
Mass: Magnetic sensor	0.65 kg
Mass: Kapvik platform	41.00 kg
Mass: Total	45.28 kg
Dimensions: Kapvik chassis	0.85 m x 0.78 m x 1.21 m
Dimensions: Wheels + Grousers	0.15 m x 0.07 m (D x W)
Dimensions: Sensor boom	0.02 m x 1.15 m (D x L)
Dimensions: Sensor cup	0.06 m x 0.05 m (D x H)
Speed	0.02 m/s
Radio Communication Range	>500 m (nominal; line of sight)
Battery Power	10 A-h (x2)

The Kapvik micro-rover (Table 2) was selected for robotic magnetic mapping due to its modular design, mobility, and a magnetically quiet composition. The Kapvik chassis, mounting plates, wheel structures, suspension, fastenings and surfaces plates are constructed from aluminum which has a low magnetic susceptibility. Active magnetic components mounted to the rover include actuators, electric motors, and

internal electronic switches. Some small ferrous steel fasteners are used to attach modules to the chassis assembly; these fasteners and other passive magnetic sources, however, are fixed in place and generate minimal magnetic interference. Kapvik's micro-rover mass budget (< 50 kg) is capable of incorporating the payload requirement of a potassium vapour magnetometer and composite boom (4.28 kg). Once instrumented, the mass of the Kapvik micro-rover is 45.28 kg.

Figure 3: AutoCAD rendering showing the Kapvik micro-rover with mounting positions of the boom and magnetometer components. The micro-rover direction of travel is denoted by the hollow white arrow. [1] Magnetometer module mounting point. [2] Composite brackets fixed to rover chassis with aluminium bolts. [3] Composite boom, 1.21 m in length. [4] Composite sensor support cup. The magnetic sensor was fixed securely in position using compressed foam spacers, plastic zip-ties and Velcro strapping. [5] Composite support struts applied for additional support and to fix boom elevation angle.

Integration of the GSMP 35U magnetometer onto the Kapvik micro-rover was accomplished by mounting the magnetometer sensor on a composite boom fixed to the

rear rover chassis as rendered in Figure 3. The Kapvik micro-rover was deployed using the configuration seen in Figure 4 with the replacement of the fore-left cylindrical sample collection bin with a counterbalanced magnetometer module. The fore-right sample collection bin was also removed from the chassis as it contained permanent magnetic sources.

Figure 4: Kapvik micro-rover, magnetic mapping configuration. The magnetometer module is shown (left) counterbalancing a boom and potassium vapour magnetometer (right). An Ethernet data and communication tether cable are seen dragging behind the rover through the grass. The micro-rover direction of travel is denoted by the hollow white arrow.

2.3.3 Composite Boom

A prototype composite boom was designed and manufactured to mount the GSMP 35U magnetic sensor on the rear chassis of the Kapvik rover. In order to optimize

boom length, static and dynamic magnetic noise tests were performed at incremental separations between the magnetic sensor and the rover chassis in the laboratory.

The fourth difference method was selected as a metric to evaluate the level of magnetic noise generated during the tests (Teskey et al., 1991; Coyle et al., 2014).

According to this method, the noise value at sample time (ΔT_0) is defined as:

$$Noise(\Delta T_0) = \frac{\Delta T_{-2} - 4\Delta T_{-1} + 6\Delta T_0 - 4\Delta T_{+1} + \Delta T_{+2}}{16}$$

where ΔT_{-2} , ΔT_{-1} , ΔT_{+1} , ΔT_{+2} are four magnetic values of the TMI sampled symmetrically with respect to ΔT_0 . An acceptable fourth difference noise limit for commercial airborne surveying is ± 0.05 nT (Teskey et al., 1991; Coyle et al., 2014).

During initial testing, the magnetic sensor was mounted on an inert plastic structure while the rover was positioned on a pedestal at 50 cm increments along a straight line away from the sensor. An activation sequence of Kapvik subsystems was initiated at each incremental distance and a fourth difference noise profile was generated. A summary of the fourth difference noise profiles generated at each distance is shown in Figure 5. A marked 60% reduction in magnetic noise over the 0.70 m and 1.20 m interval was observed whereas between 1.20 m and 1.70 m noise reduction was only a further 10%.

In a dynamic test the chassis wheels were activated for one full revolution of the wheels over a duration of 24 seconds. The test was repeated at four distances (0.2 m, 0.7 m, 1.2 m, 1.7 m). Figure 6 shows the resulting TMI data. The dynamic test confirmed the results of the initial test: noise is markedly attenuated when the distance increases

from 0.7 m to 1.2 m, but further improvement is reduced when the distance increases from 1.2 m to 1.7 m. A prototype composite boom was therefore designed and manufactured to mount the GSMP 35U magnetic sensor at a distance of approximately 1.2 m from the rear chassis of the Kapvik rover, as a compromise between noise reduction and mechanical practicality.

Figure 5: Fourth-difference noise profiles for different chassis-sensor separation distances: (a) 0.2 m; (b) 0.7 m; (c) 1.2 m; (d) 1.7 m. The noise envelopes are displayed as black dashed lines.

Figure 6: TMI responses generated by one revolution of the Kapvik chassis wheels at distances of 0.2, 0.7, 1.2 and 1.7 m from a magnetic sensor.

The tubular boom was designed with a length of 1.15 m and an internal diameter of 2 cm. Epoxy impregnated fiberglass was chosen for its strength, light weight, ease of fabrication, and low magnetic susceptibility. A cylindrical sensor support cup was fabricated from fiberglass and polyvinyl chloride (PVC) connectors, and used to vertically mount the sensor at the end of the boom at a distance of 1.21 m from the chassis.

By design, potassium vapour magnetometers operate at a prescribed optimal orientation with respect to the geomagnetic field. When the sensor is positioned close to magnetic sources, the orientation of the local field might fall outside the sensor's "active zone", causing a loss of signal. This effect has been mitigated by raising the boom by an angle of 15° to increase the distance between the sensor and the ground.

A bipod support structure was added to the design to distribute the weight of the sensor and to fix the boom elevation angle. The bipod support struts were fabricated using the same design and process as the main boom at a shortened length of 0.75 m. The boom was mounted to the chassis of the micro-rover using hybrid composite-PVC brackets. Off the shelf PVC components were selected for their modular

design, low cost, and deformability using heat treatment. They were reinforced and modified with composite to fit the chassis structure. The completed brackets were attached to the Kapvik rover using aluminum bolts already present within the structure of the chassis.

2.3.4 Magnetometer Module

The potassium magnetometer's electronic components were built into a self-contained magnetometer module whose specifications are listed in Table 3. The module, comprising the GSMP 35U electronics box, RaspberryPi2 micro-controller, serial and USB data cables, and lithium battery packs, was mounted to the rover chassis in place of a soil-sampling bin. By packaging these components as a module it was possible to replace the soil-sampling bins which were a source of magnetic noise, and counterbalance the boom-mounted sensor which proved effective for maintaining the micro-rover at a horizontal operational pitch angle.

By powering the magnetometer with a 25.9V 4000 mAh Li-battery, and using a 5 V 2600 mAh battery pack for the microcontroller it was possible to operate the module for up to 6 hours while keeping the magnetometer power supply separate from the rover subsystems.

Table 3: Magnetometer module specifications

Parameter	Value
Mass: Li-battery packs	1.26 kg
Mass: Electronics box	0.70 kg
Mass: RaspPi2 B Microcontroller	0.17 kg
Mass: Enclosure and structural foam	0.30 kg
Mass: Data cables and adapters	0.75 kg
Total Mass	3.18 kg
Dimensions	0.25 m x 0.20 m x 0.50 m
Microcontroller Battery Capacity	2600 mAh @ 5 V
Magnetometer battery Capacity	4000 mAh @ 25.9 V

2.3.5 Communications

Communication, data acquisition and magnetometer control was enabled using a RaspberryPi2 microcontroller bridged into the Kapvik network. The microcontroller was equipped with a Wi-Fi dongle and connected to the magnetometer electronics box via Serial-USB adapter. Wireless/Ethernet bridging was established to the Kapvik base station network enabling real-time data transmission and remote access to magnetometer functions. A secondary configuration was used to connect the microcontroller directly to Kapvik via the rover's Ethernet port using a data cable. This enabled the RaspberryPi2 to transmit and communicate using Kapvik's radio antenna. With this configuration the magnetometer module could be routed directly through

Kapvik's communication network. Alternately, command and control of the Kapvik rover could be routed through the micro-controller's wireless network bridge, bypassing the radio antenna. During the field survey, an Ethernet tether from the rover to the base station was employed to ensure continuity of communications to both the rover and magnetometer module.

2.4 Robotic Magnetic Survey

2.4.1 Survey Site

A robotic magnetic survey was performed with the Kapvik micro-rover in an urban environment primarily featuring local infrastructure.

The survey site consisted of a 40 m x 15 m grid located 20 m south of the Herzberg Laboratories, and 10 m west of Richcraft Hall on the campus of Carleton University as shown in Figure 7.

Figure 7: Survey grid. The position of the survey lines (white), a subsurface storm sewer (purple), adjacent gas pipe infrastructure (yellow) and the location of the Kapvik robotic base station (circled X) are marked. Background image source: Google Earth.

The survey grid was oriented perpendicular to magnetic north with the survey profile lines extending from west to east. The tie-line was surveyed from north to south. The endpoints of all lines were geolocated by GPS and marked for use as navigational aids.

Local subsurface infrastructure included a sewer line cross-cutting the survey area, and a gas line 3 m north of Line 10N. Surface infrastructure consisted of a walking pathway running parallel between Line 0N and Line 5N, a roadway to the north of L10N within 2m of the survey area, and a light rail line located 100 m to the east. In order to

mitigate interference from active cultural noise sources the survey was conducted at night when vehicle traffic on the adjacent road was reduced.

2.4.2 Data Acquisition

Kapvik was tele-operated by a human pilot via an Ethernet cable tether while recording TMI at a 10 Hz sampling rate. TMI data from each surveyed line was recorded in a separate file by the magnetometer in ASCII format and duplicated via real-time wireless transmission to an observation laptop. Each data point recorded was time-stamped by the magnetometer electronics with manually synchronized UTM timing. A log of anomalous events (such as vehicular and light rail traffic) and the time of occurrence was recorded manually.

Diurnal variations were interpolated from data recorded at the Ottawa Geomagnetic Laboratory, a magnetically quiet facility located approximately 11.5km east of the survey site. This data was referenced to the rover data by UTM synchronized time-stamp.

The 'dead-reckoned' position of the rover was determined by interpolation based upon the time required to survey each line, the GPS position of line endpoints, and a constant rover velocity of 0.02 m/s at 100% throttle. Profile line lengths were verified and marked using a 60 m fiberglass tape.

2.4.3 Magnetic Data Processing

TMI datasets for each survey line were diurnally corrected using data recorded at the Ottawa Geomagnetic Laboratory. The observatory data was generated at a 1 Hz sampling frequency which resulted in the diurnal correction algorithm correcting asynchronous data points with linearly interpolated values. These interpolated data points are considered valid due to the relatively slow rate of change of diurnal variations. The diurnally corrected data was then geolocated by stitching UTM coordinates to each data point by cross-referencing with the 'dead-reckoned' rover position dataset for each time-stamp. TMI for the three east-west lines was leveled by linear interpolation using tie-line intercept values and plotted to generate a spatially referenced magnetic dataset as shown in Figure 8. The amplitude of local variations within the dataset was emphasized through normalization by removal of the ambient regional magnetic field of 52500 nT, and the application of a linear compensation to remove a 41 nT/m local trend, decreasing towards geographic north, from the dataset. This gradient was due in large part to significant infrastructure present adjacent to the survey grid (buildings, roadways). The resultant residual magnetic intensity grid was cropped to eliminate edge effects and a Delaunay triangulation (Lee & Schachter, 1980) was applied to interpolate the data with respect to position.

Figure 8: Scatterplot of TMI versus geographical position, a regional gradient is present within the data. The Kapvik robotic base station was positioned at [-22,-7] (star symbol) and may have contributed to anomalous values observed at the western line endpoints.

2.4.4 Fourth Difference Analysis

The fourth difference method was applied to evaluate the level of magnetic noise during rover operations. Noise profiles calculated using the fourth difference method display discontinuous noise as isolated spikes or a series of closely-spaced spikes forming a wavetrain, and display continuous noise as a swath of consistent frequency. Spikes can be the result of external sources such as passing vehicles, DC sources (switches), crew-rover interactions, or spherics. Continuous noise may be attributed to vibrations affecting the sensor, oscillations of the rover attitude, ambient background noise of a specific frequency (such as interference by powerlines) or other periodic influences. The fourth difference noise profile of Line 10N is chosen as an

example to show the appearance of discontinuous noise sources (spikes) resulting from passing vehicles (Figure 9). A detailed recording of all vehicles passing within view of the survey site for Line 10N is presented in Table 4. The large spikes in the noise profile correlate well to the times at which vehicles passed in the vicinity of the survey site. Discounting the spikes, the noise envelope was estimated at $\pm 0.03nT$. This noise envelope takes into account the ambient background noise, interference from robotic components, and noise generated by the roving motion of Kapvik.

Table 4: Cultural noise sources logged during data acquisition along Line 10 N.

Time (s)	Mobile sources of interference	Distance from source to Kapvik (m)
124	Small vehicle	5
150	Train	130
155	Small vehicle	5
451	Small vehicle	10
506	Small vehicle	10
613	Small vehicle	12
770	Small vehicle	13
881	Small vehicle	15
907	Train	118
937	Small vehicle	15
961	Small vehicle	15
1014	Small vehicle	16
1046	Small vehicle	16
1056	Train	116
1100	Small vehicle	17
1141	Small vehicle	17
1183	Small vehicle	18
1281	Large vehicle	80
1316	Small vehicle	20
1341	Small vehicle	20
1414	Small vehicle	20
1455	Large vehicle	20

Figure 9: Fourth difference noise profile of line 10 N. The estimated noise envelope of ± 0.03 nT is shown as dashed horizontal lines.

2.4.5 Spectral Analysis

A discrete Fourier transform was applied to evaluate the spectral density of the magnetic data acquired during selected rover operations. 2500 time-series data points acquired at a 10 Hz sampling frequency were normalized, had a linear trend removed, and then used as input values to generate spectra. These spectra were calculated using overlapping fast Fourier transform segments of 500 data points with a Hanning window and then averaged to generate the linear spectral density response (Heinzel et al., 2002). The resulting linear spectral density spectra describe the magnitude of the magnetic response in the frequency range of 0-5 Hz.

Figure 10 displays a comparison between spectra generated during active and passive testing of the chassis wheel rotation within a laboratory setting. A broad

spectral response from 0-1 Hz with additional harmonics of a 0.125 Hz base frequency are noted within the dataset during activation of the chassis wheels. These readings were acquired within a magnetically noisy laboratory setting with a correspondingly elevated noise floor.

Figure 10: Linear spectral density plot of the Kapvik chassis wheel rotation response.

The spectral response of the micro-rover under field survey conditions is shown in Figure 11. The ambient background spectra again displays a clear harmonic with a base frequency of 0.125 Hz. The mobile rover spectra generates a broad spectrum response throughout the spectral range of 0-5 Hz as shown by the vertical offset. The difference in spectra response is primarily noted between 0-1 Hz, 2.66 Hz, 3.66 Hz, and 4.5 Hz where the variation is greatest. While the robotic survey site did have a lower ambient noise level when compared to the laboratory conditions, it should be noted

that the ambient spectral noise is higher than would be expected of a non-urban survey environment.

Figure 11: Linear spectral density plot of robotic survey data.

At a roving speed of 0.02 m/s, the magnetic response generated by environmental sources is generally expected to appear within the 0-1 Hz frequency range. Kapvik's wheels rotate with a period of approximately 22 seconds under survey conditions, at a frequency of approximately 0.045 Hz. A harmonic drive built into Kapvik's motor-gear assembly includes a wave generator containing ferromagnetic ball bearings (Ellery, 2015). With a gearing ratio of 1:100 this component rotates at 100 times the period of the wheels and may be attributed to the spike at 4.5 Hz observed within the active rover spectra.

2.4.6 Interpretation and Discussion

Figure 12: Delaunay triangulation of residual magnetic intensity. A dipole 650 nT in amplitude corresponds to a linear anomaly in the centre of the grid.

From the interpolated map of the residual magnetic intensity seen in Figure 12 an anomalous dipole response of 650nT describing a linear feature is clearly apparent in the center of the grid. This anomaly coincides with the known position of a storm sewer buried at a depth of approximately 2 m as indicated on campus infrastructure service plans. A follow-up visual inspection of the small escarpment adjacent to the river south of the survey grid confirmed the presence of a ferromagnetic pipe at 2 m depth within the confines of the grid.

During the survey, the Kapvik micro-rover demonstrated that its rocker-bogie suspension caused negligible vibrations and physical oscillations acting upon the potassium sensor. The integrated systems operated within a noise envelope of ± 0.03 nT under field conditions, when the rover was moving at its maximum speed of 0.02 m/s,

via tele-operation. Based on laboratory tests (section 2.4.3), the rotation of the wheels was the largest source of continuous noise. Cultural responses observed from passing vehicles, especially trains, generated the highest amplitude discrete sources of noise.

2.5 Concluding Remarks

2.5.1 Future Work

In the future, not only the impact of each subsystem on magnetometer readings should be assessed more rigorously in isolation and in controlled conditions, but their combined impact also needs attention. Employing operation methodologies where a magnetic offset is measured during activation of additional subsystems is essential. By returning subsystems to a standard reference configuration the uncertainty related to magnetic offsets can be reduced significantly.

Scientific instruments such as ground penetrating radars (Ciarletti et al., 2011; Hamran et al., 2015) and electromagnetic induction sounders (Boivin et al., 2013) actively emit electromagnetic signal as part of their standard operations. The same can be expected from other active scientific instruments mounted on the rover such as the articulated arm and end effector instrumentation.

Results of this preliminary robotic survey open several lines of investigation for future applications of micro-rovers for planetary exploration. The GSMP 35U magnetometer used in this study has been optimized for the range of magnetic field intensities typically encountered in terrestrial environments (15,000 to 120,000 nT). This

operational range is atypical of other planetary bodies within the solar system and would limit the use of the magnetometer to terrestrial qualification applications. A second limiting factor for the use of this magnetometer in extraterrestrial environments is the relatively large power required to maintain thermal stability. Alternate magnetometers need to be tested for the TMI range expected during a planetary mission. This range would vary according to the planetary body under consideration.

Finally, not all magnetic data acquired by the rover needs to be telemetered to Earth-based operators. A mapping mission would benefit from onboard algorithms and sufficient processing power to allow the rover to survey with some degree of autonomy (Castano et al., 2007; Woods et al., 2009; Gallant et al., 2013). If robotic magnetic mapping is done as part of regional scouting for targets of astrobiological interest, change detection algorithms would only alert operators if there is a departure from baseline readings. To maximize opportunity for science, algorithms could be developed to guide the rover to survey in the direction corresponding to the highest spatial gradient of the magnetic field.

2.5.2 Summary of results

This study focused on rover-magnetometer integration. The global impact of the rover on magnetic data was first considered and distance tests were performed to determine the optimal boom length. A length of 1.2 m was selected as a compromise between reducing noise and mechanical stability. Further tests sought to isolate the effect of different noise sources. Despite these rover-related sources of noise and additional cultural noise present in the urban environment where the field survey took

place, the noise envelope of field data was ± 0.03 nT during nighttime operations. As a point of comparison, a noise envelope of ± 0.05 nT or less is considered acceptable for commercial airborne magnetic surveys (Coyle et al., 2014). The relatively low level of noise of the magnetic data recorded by the Kapvik micro-rover is mostly due to its very slow speed. The magnetic data acquired during the robotic survey identified an anomalous linear feature corresponding to a magnetic dipole 650 nT in amplitude. The system should be capable of detecting much more subtle targets.

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Magnetic Mapping with an Uninhabited Ground Vehicle

3.1 Introduction

The magnetic method is a widely-used geophysical surveying technique used to map broad geological trends, detect ore bodies, or locate discrete magnetic sources. It is applied at different scales from large national territories to small prospective mining properties. To meet these different demands, magnetometers are deployed from a variety of platforms. They can be mounted on manned helicopters and fixed-wing aircraft for airborne operations, towed behind ships, carried by ground crews, and, more recently, used remotely with the development of uninhabited air vehicles (UAVs). A new generation of light-weight magnetometers have been designed to meet the needs of the emerging UAV market. A novel opportunity exists for the instrumentation of uninhabited ground vehicles (UGVs) with UAV magnetometers for robotic surveying.

UGVs expand the range of geophysical surveys into environments which are less suited to traditional terrestrial methods. Under remote or autonomous operation a UGV can deliver geophysical sensors into hazardous or difficult to access environments such as mine tailings deposits (Olmedo & Lipsett, 2016) or underground tunnels. By removing human operators from the survey area UGVs can address niche applications, reduce

risk, and extend coverage. A niche application suited to UGVs is unexploded ordnance (UXO) detection, characterization, and mapping. UGV systems instrumented with electromagnetic sensors have proven highly effective at locating conductive targets in the near subsurface (Khamis, 2013; Grusy, 2009).

To explore the potential of UGVs for mapping of the near subsurface using the magnetic geophysical method, a commercial UGV, the Husky A200 robotic development platform from Clearpath Robotics, was instrumented with the recently developed GSMP 35U potassium vapour magnetometer from GEM Systems. The objectives of the study were to determine the impact of the magnetic UGV components on sensor data quality, to integrate the magnetometer and UGV in a practical configuration, and to evaluate the capability of the instrumented Husky UGV to perform magnetic geophysical surveys. A key issue was the interference caused by the UGV platform on the magnetic data. To minimize interference, a mounted tower design was implemented to increase the distance between the magnetometer and the magnetically susceptible components of the Husky UGV. The integrated Husky UGV was used to perform two comparative robotic magnetic surveys while mapping cultural targets and regional variations of the magnetic field.

3.2 Instrumentation and Hardware

3.2.1 Magnetometers

Total magnetic intensity (TMI) data was acquired in this study using a GSMP 35U potassium magnetometer in mobile operation and a GSM-19 Overhauser magnetometer deployed as a base station (

Table 5). Both magnetometers are designed to measure the total magnetic field B as a scalar value (Kearey et al., 2002). The GSMP 35U potassium vapour magnetometer was selected for integration with the Husky UGV platform due to its low weight, reduced dimensions, high sensitivity, and rugged design (Hrvoic & Hollyer, 2015). With a 10Hz sampling frequency, this magnetometer was well suited to maintain a high spatial resolution during survey operations. A GSM-19 Overhauser magnetometer was selected for use as a stationary base station. Due to the lower frequency of diurnal variations a 0.33 Hz sampling frequency and ± 0.10 nT accuracy were sufficient for monitoring the magnetic background and to determine the diurnal corrections to be applied to survey data.

Table 5: Magnetometer specifications.

Parameter	GSMP 35-UAV	GSM-19
Type	Potassium vapour	Overhauser effect proton precession
Sensor Mass	0.65 kg	1.00 kg
Electronic Box Mass	0.63 kg	2.10 kg
Sensor Dimension	158 mm x 64 mm	177 mm x 75 mm
Electronic Box Dimensions	237 mm x 56 mm x 39 mm	223 mm x 69 mm x 240 mm
Sensitivity	0.0003 nT @ 1Hz	0.22 nT / $\sqrt{Hz}$
Resolution	0.0001 nT	0.01 nT
Absolute Accuracy	+/- 0.05 nT	+/- 0.10 nT
Dynamic Range	15,000 to 120,000 nT	20,000 to 120,000 nT
Gradient Tolerance	50,000 nT/m	< 10,000 nT/m
Sampling Frequency	10 Hz	0.33 Hz

3.2.2 Husky Uninhabited Ground Vehicle

The Husky A200 robotic development platform is an all-terrain UGV designed for rapid prototyping and research applications (Figure 13; **Error! Reference source not found.**).

The platform features a rugged design, onboard power supply, aluminum mounting rails, and open-source operating system (Clearpath Robotics, 2015). The robotic platform was selected for terrestrial magnetic mapping due to its 1.0 m/s top speed, 75 kg payload rating, and slip-drive mobility system. Functionally, its skid-steer drive performs

well in diverse terrain conditions with high-torque electric motors that are capable of pushing through challenges such as light brush, rocks, loose gravel slopes, mud and flooded fields which were encountered in the field. The 75 kg payload budget of the UGV was large enough to easily incorporate the mass of the potassium magnetometer, aluminum tower and electronics modules with negligible impact on mobility performance. The instrumented rover was deployed in survey configuration (Figure 13); a field laptop was employed for troubleshooting but was not integral to the operation of the system.

Table 6: Husky A200 micro-rover specifications.

Parameter	Value
Mass: Magnetometer Module	3.18 kg
Mass: Sensor Tower	0.40 kg
Mass: Magnetic Sensor	0.65 kg
Mass: Husky Chassis	50.00 kg
Total UGV Mass	54.23 kg
Dimensions: Husky Chassis	0.99 m x 0.67 m x 0.39 m
Dimensions: Sensor Tower	0.15 m x 0.30 m x 1.40 m
Speed	1.00 m/s
Wi-Fi Communication Range	50 m
Power	24 V 20 Ah Sealed Lead Acid Battery

Figure 13: Photograph of the Husky A200 UGV in survey configuration.

3.2.3 Operations Module

Command and control of both the magnetometer and UGV were accomplished using an operations module built into the cargo bay of the UGV (Table 7). This module comprised the magnetometer electronics box, data cables, lithium batteries and a RaspberryPi2 microcontroller. A customized foam spacer was employed to channel cables and position the module's components securely within the cargo bay. A key feature of the operations module was the application of a RaspberryPi2 microcontroller to miniaturize computing resources and simplify command and control. The robot operating system (ROS) was modified to operate on the embedded microcontroller's reduced resources and configured to enable teleoperation either by wireless connection or tethered USB joystick. A RaspberryPi3 microcontroller was later implemented within the operations module to log magnetic data from the magnetometer electronics box and to wirelessly broadcast real-time data to the operator.

Table 7: Operations module specifications.

Parameter	Value
Mass: Li-battery Packs	1.46 kg
Mass: Electronics Box	0.70 kg
Mass: Raspberry Pi 2 & 3 Microcontrollers	0.34 kg
Mass: Data Cables and Adapters	0.75 kg
Mass: Total	3.35 kg
Cargo Bay Dimensions	0.297 m x 0.421 m x 0.155 m
Microcontroller Battery Capacity	2600 mAh @ 5 V
Magnetometer Battery Capacity	4000 mAh @ 25.9 V

3.2.4 Sensor Tower

A tower was built to mount the survey magnetometer at a vertical distance of 121 cm from the top of the chassis along the z-axis (vertical axis centered on the UGV). From preliminary testing it was noted that vertical oscillations of the sensor would be magnified by the lack of UGV suspension if combined with the leverage of a long boom, an effect which had been noted on other boom-mounted UGV systems (Phelps et al., 2014). This is why a tower was preferred over a boom to provide vertical support and mitigate vertical oscillations of the sensor during travel along profile lines.

The tower was composed of a framework of vertical aluminum rails bolted to 3 horizontal frames using brass screws to form a semi-rigid lattice structure. Cross braces were applied to the vertical rails to strengthen the structure and reduce vibration during motion of the platform. Bands of duct tape were used to apply compressive tension to the aluminum framework and structure to mitigate the transmission of vibrations generated by the UGV traversing rugged terrain.

The base of the tower was secured to the UGV with four thumb screws bolted to the chassis' aluminum mounting rails. The survey magnetometer was mounted atop the tower in a vertical orientation and affixed with hook-and-loop straps, cable ties, and electrical tape. The elevation of the magnetic sensor was 160 cm relative to ground level when mounted to the UGV, a height comparable to that used by ground survey crews.

3.3 UGV Magnetic Signature

3.3.1 Magnetic mapping of the UGV

The chassis, mounting rails, bumpers, and plating of the UGV are composed of lightweight aluminum which has a low magnetic susceptibility. Components containing ferrous materials included the wheel rims, axles, and electric motors. These components have a high magnetic susceptibility and are not ideal for robotic magnetic surveying. Tests were therefore performed in a laboratory setting to measure the influence of UGV components on the magnetic sensor. Magnetic scans were performed to identify regions of elevated magnetic intensity generated by the UGV platform at various

orientations and distances from the survey magnetometer. A rail-mounted GSMP 35U magnetometer was used to measure TMI along the length of the chassis (x-axis) at a vertical separation distance of 33 cm above the rover chassis (z-axis) for a series of traverses spanning the width of the UGV (y-axis) (Figure 14). The UGV would then be repositioned with the same orientation and a 10 cm incremental offset in the y-direction before the scanner would again traverse the rail. Data acquisition along each traverse generated a 1-D magnetic profile of the UGV. The series of profiles were corrected for diurnal variation. The background (no UGV present) was subtracted from the data which was then input to a Delaunay triangulation (Lee & Schachter, 1980). In this fashion, 1.10 m x 2.00 m 2-D scanned maps of the UGV were constructed.

Figure 14: Magnetic scanning equipment set up. Traverses by the scanning cart along the rail (hollow arrow) were reversed for each subsequent scan. The X-axis is parallel to the rail, the Y-axis is oriented into/out of page, and the Z-axis is oriented vertically.

Two scans of the UGV were collected. The first scan was undertaken while the UGV was powered with the electric motors disconnected from the onboard battery power using an emergency-stop switch. The corresponding magnetic map represents the passive remnant magnetic field of the UGV (Figure 15 (a)). It shows a positive 200 nT magnetic response above the front and rear axles, and a 250 nT negative magnetic response centered on the UGV cargo bay. The second scan was undertaken with the

electric motors reconnected to the onboard battery power at 0% throttle**Error!**

Reference source not found.. A 2500 nT/m gradient is readily apparent in the corresponding magnetic map with minor fluctuations being noted above the UGV axle positions (Figure 15 (b)). This sizable DC field has been attributed to the 2 electric motors which have been mounted to the chassis parallel to the axles in a mirrored opposite orientation.

Figure 15: Map of the total magnetic intensity of the UGV with electric motors: (a) disconnected from the onboard battery power, and (b) connected to onboard battery power at 0% throttle (idle). The position of the Husky UGV is outlined in black. Note that the TMI scale is different by one order of magnitude for the two scenarios.

3.3.2 Magnetometer-UGV separation tests

TMI decreases at a rate of $1/r^3$ where r is the distance between the magnetometer and the magnetic source. To inform the choice of the height of the sensor tower, tests

were conducted to assess the level of noise associated with the UGV chassis wheels which are composed of steel rims with rubber tires, attached to steel axles by aluminum brackets and screws. During rotation of the chassis wheels, the TMI was recorded over a period of 20 seconds at several separation distances between the UGV chassis and the survey magnetometer (Figure 16; Figure 17). Based on the results of these tests, a distance of 121 cm was selected for the tower design as a compromise between noise reduction, selection of available aluminum rail framework, and mechanical practicality (Figure 18).

Figure 16: Separation test set-up. (Left) TMI was measured at various distances from a magnetometer mounted on a tripod. (Right) During testing the UGV was “up on blocks” allow the wheels to rotate. The magnetometer remained in a stationary position to isolate the ambient magnetic background from the UGV response.

Figure 17: Magnetic oscillations generated by the chassis wheels during full revolution at 1.0 m/s. Magnetometer-UGV separation distances: (A) 41 cm, (B) 60 cm, (C) 89 cm, (D) 105 cm, (E) 150 cm, (F) 200 cm. The influence of ambient background magnetic signals on the TMI can be seen in (E) at 15 s. Cultural sources were common within the campus environment and have been removed where possible.

Figure 18: Amplitude of magnetic oscillations generated by the chassis wheels versus magnetometer-UGV separation distances. The selected separation distance of 121 cm is noted by the red dot which corresponds to a TMI oscillation amplitude of ± 7 nT.

To guide future design changes, a related test was performed at a separation distance of 121 cm without the chassis' steel wheel rims in place to isolate the impact of the rotation of the rims on the amplitude of magnetic oscillations (Figure 19). By removing the steel wheel rims from the UGV a notable 84% reduction in oscillation amplitude was observed. The use of rims made of a magnetically inert material would be a simple solution to reduce the magnetic signature of the UGV in future applications.

Figure 19: Reduction in the amplitude of magnetic oscillations achieved by removing the steel wheel rims. TMI of the rims and axles is shown in blue; TMI of the axles alone is shown in red.

3.3.3 Fourth Difference Analysis

To add a different perspective to noise analysis, the fourth difference method was selected as a metric to evaluate the level of magnetic noise. According to this method, the noise value at sample time (ΔT_0) is defined as:

$$Noise(\Delta T_0) = \frac{\Delta T_{-2} - 4\Delta T_{-1} + 6\Delta T_0 - 4\Delta T_{+1} + \Delta T_{+2}}{16}$$

where ΔT_{-2} , ΔT_{-1} , ΔT_{+1} , ΔT_{+2} are four values of the TMI sampled symmetrically with respect to ΔT_0 . An acceptable noise limit for commercial airborne surveys calculated using this method is ± 0.05 nT (Teskey et al., 1991; Coyle et al., 2014). The noise level was quantified by determining the value of two standard deviations of the fourth difference noise which defined the noise envelope.

Fourth difference noise profiles were generated from all laboratory and field datasets to determine which factors would result in an increase in magnetic noise levels. The factors which were evaluated included magnetometer-UGV separation, the effect of wheel rotation, and vibration and mechanical noise related to the velocity of the UGV during survey operations. Environmental noise from outside sources, such as cultural noise from passing vehicles, was difficult to control and could only be mitigated by conducting tests and surveys during less active hours. This was a primary concern in the urban environment of Carleton University campus.

Figure 20: Fourth difference noise profiles generated from the TMI time series presented in Figure 17.

Magnetometer-UGV separation distances: (A) 41 cm, (B) 60 cm, (C) 89 cm, (D) 105 cm, (E) 150 cm, (F) 200 cm.

Vertical scales have been magnified at increasing distances to better display the signal. The influence of ambient background noise can be seen in (E) at ~15 s. This type of spike in noise was common within the campus environment and has been removed where possible.

The fourth difference determined from magnetometer-separation test data confirms that increased separation distance greatly reduces the amplitude of the noise (Figure 20). With the sensor positioned at a distance of 41 cm of the UGV, the noise level is ± 1.5 nT. As the sensor is positioned at a greater distance from the UGV chassis, the noise level is rapidly reduced by 80% to ± 0.30 nT at 89 cm. It falls to ± 0.10 nT at the selected 121 cm separation which represents a 93.3% reduction in noise over an 80 cm increase in separation from the 41 cm case.

The fourth difference method was also used to investigate in detail the impact of wheel rotation on noise (Figure 21). The rotation period of the chassis wheels is manually controlled by varying the current applied to the electric motors in increments of 10% throttle via the tethered joystick. The wheels of the Husky UGV rotate with a period of approximately 2.63 s while at an electronically limited 40% throttle; this setting corresponds to the limited half-speed of 0.4 m/s. The pilot can manually override the throttle limiter with an electronic switch to increase the rotation period of the wheels to approximately 1.03 s when the electric motors are at 100% throttle. The UGV then travels at a full-speed of 1.0 m/s. At a magnetometer-UGV separation distance of 121 cm, the steel wheel rims and axles were found to generate ± 0.10 nT of noise during full-speed rotation. With the steel wheels removed, the axles were found to generate 30% less noise at ± 0.07 nT. The speed at which the wheels were rotating was also found to have a significant effect on the noise profile as can be seen in the difference between Figure 21 (A) and Figure 21 (C). At half-speed, since the wheels only complete half a rotation per second, the fourth difference method, which uses 5 sequential

readings spaced by 0.1 ms in time for a total duration of 0.5 ms, only captures a portion of the wheel rotation.

Figure 21: Fourth difference noise profiles during Husky wheel rotation testing (Figure 19). (A) Noise generated by rims and axles at full-speed (1.0 m/s), (B) noise generated by axles at full-speed, (C) noise generated by rims + axles at half speed (0.4 m/s).

3.3.4 Spectral Analysis

Fourier spectral analysis was used to determine the magnetic signature of the UGV in the frequency domain. Time series of 501 sequential data points sampled at 10 Hz were extracted from TMI laboratory datasets, normalized, corrected to remove linear trending, and then used as inputs in a fast Fourier transform algorithm to generate frequency spectra. The oscillations generated by the rotation of the steel wheel rims and axles have distinct spectral responses according to their periodicity (Table 8). Figure 22 (a) displays the spectrum generated by the wheels rotating at 40% throttle (blue). The fundamental spectral peak is at 0.38 Hz (corresponding to a period of 2.63 s for the wheel revolutions) and the first harmonic peak is at 0.78 Hz, twice the fundamental frequency. The spectrum generated when the steel wheels are removed (red) also shows a peak at 0.38 Hz although at 9 dB lower maximum amplitude. The same trend is observed in the spectrum generated by the wheels rotating at full-speed with 100% throttle (Figure 22 (b)). The fundamental spectral peak is at 0.97 Hz (corresponding to a period of approximately 1.03 s for the wheel revolutions) and the first harmonic peak at 1.94 Hz. There is a similar amplitude reduction of 9 dB when the steel wheel rims are removed.

Table 8: Husky wheel rotation parameters.

Electric Throttle (%)	Fundamental frequency (Hz)	Fundamental period (s)	UGV Survey Speed (m/s)
40	0.38	2.63	0.40
100	0.97	1.03	1.00

Figure 22: Frequency spectra of TMI time series when wheel rims are attached (blue) or removed (red) from axles, for rotation speeds of (a) 0.4 m/s and (b) 1.0 m/s. The spectral response of the ambient background in the laboratory is also plotted for reference (black).

3.4 Carleton Campus Robotic Magnetic Survey

3.4.1 Survey Site

A robotic magnetic survey was performed with the Husky UGV in an area of the Carleton University campus previously surveyed by the Kapvik planetary exploration micro-rover (Hay et al., 2017). In addition, a walking ground survey with human operator was also conducted at this site but due to high field gradients and the variable walking motion resulted in a dataset which was not suitable for comparison. The survey site consisted of a rectangular 45 m x 12 m grid centered 40 m southeast of Herzberg Laboratories and 25 m southwest of Richcraft Hall (Figure 23). Local infrastructure consisted of a buried storm sewer and a gas pipeline, surface walking paths traversing the middle of the grid, and an adjacent roadway. A light rail line is located 100 m east of the grid.

The grid layout consisted of five 45 m long survey profile lines at a 3 m line spacing oriented east-west with respect to magnetic north. Two 12 m long tie lines at the profile line end-points were oriented north-south. Profile lines distances were measured manually using a fiberglass tape and line end points were marked with pylons for use as navigational aids.

Figure 23: Carleton campus survey grid. The positions of the profile (L 0N, L 3N, L 6N, L12N) and tie (T 0E, T 45E) lines (white), a subsurface storm sewer (purple), and a gas pipeline (yellow) are marked. Background image source: Google Earth. Gridlines were oriented with respect to magnetic north (MN) at 13.3° W declination from the orientation of geographical north (star).

3.4.2 Data Acquisition

The survey was conducted during weekday daylight hours. Mitigation of cultural noise sources was accomplished by waiting for local traffic patterns to slow before rapidly completing each line segment. This strategy took advantage of the fact that, at an operational speed of 1.0 m/s, the UGV only took approximately 45 s to cover a profile line.

The UGV was tele-operated by a human pilot tethered by USB joystick, following at a distance of 2 m behind. A handheld GPS unit placed in the UGV cargo bay was used to log the position at a 1 Hz sampling frequency and ± 3 m accuracy. TMI data was recorded at a 10 Hz sampling frequency and recorded by the magnetometer in ASCII format. All recording equipment was manually synchronized to coordinated universal time (UTC) prior to the survey and each data point was timestamped so that datasets could be stitched together in post-processing.

3.4.3 Data Processing

The initial TMI dataset acquired by the UGV was diurnally corrected using data recorded at the Ottawa Geomagnetic Laboratory, a magnetic observatory located 11.5 km east of the survey site. The observatory data was generated at a 1 Hz sampling frequency, which resulted in the diurnal correction algorithm correcting asynchronous data points with linearly interpolated values. The diurnally corrected data was geolocated by stitching the corresponding GPS coordinates to each data point based upon a common UTC timestamp. The TMI for each of the profile lines was then levelled by linear interpolation using tie-line intercept values and normalized by removal of the ambient regional magnetic field intensity of 52500 nT (see the example of line L 3N in Figure 24). A 41 nT/m local trend, decreasing towards geographic north, was also removed from the dataset. This gradient was due in large part to infrastructure present adjacent to the survey grid (buildings, roadways) which heavily influenced the local magnetic field. The resultant residual magnetic intensity grid (Figure 25) was cropped to

reduce edge effects and a Delaunay triangulation (Lee & Schachter, 1980) was applied to interpolate the data with respect to position (Figure 26).

Figure 24: Post-processed TMI profile for line L 3N. Sinusoidal oscillations in the data are attributed to the rotation of the UGV wheels.

Figure 25: Residual magnetic intensity scatterplot of the Carleton campus survey grid.

Figure 26: Residual magnetic intensity map, after interpolation using a Delaunay triangulation.

3.4.5 Interpretation and Discussion

The interpolated residual magnetic intensity map (Figure 26) outlines a linear anomaly trending parallel to magnetic north. This feature has a maximum amplitude of 625 nT at location (-2 m, -5 m) which corresponds to the known position of a subsurface storm sewer. The spatial resolution of the Husky UGV surveying at a velocity of 1.0 m/s with a magnetometer sampling rate of 10 Hz is 0.1 m which was more than sufficient for detecting the anomalous cultural sources present in the near subsurface. The impact of the oscillations generated by the Husky wheels and magnetic components is clearly displayed as a rippled texture overlaying the interpolated data set. This texture blurs the appearance of transitions of the magnetic intensity and may obscure weak responses or the position of small discrete features.

Figure 27: Fourth difference noise profile for line L 3N. The noise envelope is displayed as a black dashed line.

Each line segment was analyzed using the fourth difference method to generate a noise profile. Figure 27 displays an example from line L 3N of the noise level generated by the UGV during active survey operations at a velocity of 1.0 m/s. During line traverses the noise level was ± 2.5 nT. This level of noise was notably higher than the ± 0.1 nT level of noise observed during the wheel rotation tests for a speed of 1.0 m/s in the

laboratory. The increased noise level is attributed to vibrations generated by the mechanical interaction of the ground with the wheels and geological magnetic noise from small disseminated sources.

Previously a magnetic survey of the Carleton University campus was completed with the Kapvik micro-rover at a similar location (Hay et al., 2017). The results generated by the two surveys are summarized in Table 9. The magnetic responses for the two surveys generated data sets with TMI ranges of 754 nT for the Kapvik micro-rover and 673 nT from the Husky UGV. The 650 nT anomalous linear response attributed to a buried storm sewer by the Kapvik micro-rover was detected at the same position by the Husky UGV at 625 nT, although at a much lower spatial resolution. During survey operations the primary active component on each rover was the rotation of the chassis wheels. On the Husky UGV the wheels were found to generate much higher magnetic interference due to the combination of a ferromagnetic composition of the wheels and a survey speed 20 times faster than the Kapvik micro-rover. This generated a noise profile which was two orders of magnitude greater for the Husky UGV. For the identification of relatively large near-surface cultural targets the Husky UGV was sufficient to the task; with a survey production speed nearing 1000 m/h it was also a more practical choice.

Table 9: Comparative results between UGV magnetic surveys of Carleton University campus grid.

Parameter	Kapvik	Husky
Survey Speed (m/s)	0.02	1.00
Surveyed Distance (line m)	135	249
Spatial Resolution (m)	0.002	0.1
Survey Duration (min)	225	15
Productivity (line m / h)	36	996
Magnetometer-UGV Separation (cm)	121	121
Maximum TMI Recorded (nT)	418	522
Minimum TMI Recorded (nT)	-336	-152
Fourth-difference Noise (std dev) (nT)	± 0.03	± 1.97

3.5 Hay Bay Robotic Magnetic Survey

3.5.1 Survey Site

A robotic magnetic survey was conducted with the Husky UGV, in parallel with a human operated walking survey, in the rural township of Greater Napanee, Ontario, Canada, to allow a comparison between both datasets. Another objective of the survey was to demonstrate the terrainability of the Husky UGV and measure its impact on data quality.

The survey site consisted of three neighbouring properties defining a 200 m x 200 m area bounded to the north by Lennox and Addington County Road 9, between #5255 and #5268, and bounded to the south by the shoreline of Hay Bay (Figure 28).

The survey area was a mixture of agricultural gardens, lightly wooded copses, and open clearings. The topography consisted of an elevated northern plateau and a southern flood plain adjacent to the Bay, divided by a steep slope trending northeast across the center of the site. Local infrastructure consisted of stationary agricultural equipment, 3 large residences, several smaller outbuildings, and intermittent fencing oriented perpendicular to Lennox and Addington County road 9.

Figure 28: Hay Bay site map. Borders of the survey area are outlined by a dashed yellow line. The position of Well 1 and Well 2 (red markers), and the magnetic base station (circled X) are marked. Well 3 is located off-map 100 m west along the road. A solid white line marks the position of a survey line which was common among all surveys, referred to as the “common reference line”. The declination angle between magnetic north (MN) and geographical north (star) is 12.2° W. Background image source: Google Earth.

The local bedrock of the region is a limestone sedimentary strata overlain by clay and silica-rich sediments. Local well logs were available (Table 10, Table 11, Table 12), which define a depth to bedrock of between 1.54 m to the north of the grid and 3.66 m along the shoreline (Government of Ontario, 2013).

The site was surveyed without a set grid structure. Instead, semi-parallel profile lines were traversed in an orientation perpendicular to magnetic north where access was available. Tie lines oriented parallel to magnetic north were not employed for this survey due to the presence of a steep escarpment and cultural barriers which restricted access. Profile line spacing ranged from 10 to 20 m.

Table 10: Well 1 - Shoreline log results. Lat: 44.144544, Lon: -76.991695.

Layer Thickness (m)	Material
0 - 3.6576	Topsoil
3.6577 - x	Limestone

Table 11: Well 2 - Shoreline log results. Lat: 44.142378, Lon: -76.992009.

Layer Thickness (m)	Material
0 - 0.30	Topsoil
0.30 – 2.10	Clay
2.10 – 6.55	Limestone

Table 12: Well 3 - County road 9 log results (north and west of site). Lat: 44.145328, Lon: -76.995786.

Layer Thickness (m)	Material
0 – 1.54	Topsoil
1.55 – 18.29	Limestone

3.5.2 Data Acquisition

A preliminary survey of the site was conducted on March 26th, 2016, by walking the GSMP 35U magnetometer mounted on a pole 160 cm in height while recording the TMI at a 10 Hz sampling frequency. A handheld GPS unit was employed to track the position of the operator and to help navigate by maintaining an east-west heading. UTC timing was used to synchronize the timestamps between the survey magnetometer, base station magnetometer, and GPS unit. Pylons were used as navigational references to guide the path of the operator along the common reference line. Profile paths were navigated by deviating around obstacles where required.

A follow up survey of the same site was completed on April 26th, 2016 with the Husky UGV following a similar path selection strategy. The UGV was teleoperated by a human pilot using a USB joystick and following at a distance of 2 m. The common reference line was surveyed, after which the rover was piloted wherever site access would allow easy passage. The tracks left by the UGV wheels were used to navigate subsequent parallel traverses of the east-west profile lines. Consecutive lines were surveyed whenever a straight path could be navigated; the longest potential lines were

surveyed with the greatest priority. Coverage of the survey site was split between operations at the full-speed of 1.0 m/s in the north-eastern quarter, at the half-speed of 0.4 m/s in the north-western quarter, and with coverage at both speeds in the southern half of the site.

3.5.3 Data Processing

Data for the diurnal correction was obtained from a base station magnetometer located within a magnetically quiet area of the survey site where the local gradient was less than 1 nT/m (as marked by the circled X in Figure 28). The diurnally-corrected TMI dataset was then stitched with the time stamped GPS coordinates for geolocation. Intersection points between profile line crossings were compared to determine where levelling was necessary. Segments of the dataset were cut where signal quality was reduced or where a magnetic signal lock had been lost. These segments were close to cultural sources. To compare datasets gathered on different days a DC-shift was applied to normalize the average TMI of the three surveys. The resultant TMI datasets were used to generate scatter plots for the walking survey and the combined UGV survey (Figure 29).

Figure 30 displays TMI and corresponding fourth difference noise profiles taken from representative segments of the common reference line surveyed by different methods. Time series of 501 sequential data points from the common reference line

were also used to determine the frequency content of the magnetic signal using a fast Fourier transform (Figure 31).

Figure 29: TMI scatter plots - Hay Bay. Walking survey (top), combined UGV survey (bottom).

Figure 30: TMI (left) and fourth difference noise profile (right) comparison between 3 operational modes. Human operated (A/B - Top), Husky UGV operated at 0.4 m/s (C/D – middle) and 1.0 m/s (E/F - bottom).

Figure 31: Frequency spectra of TMI time series from the common reference line.

3.5.4 Interpretation and Discussion

The scatter plots generated during the walking survey and the combined UGV survey (Figure 29) show similar characteristics with a few notable differences. Both scatterplots show a regional gradient of 3.15 nT / m increasing to the south west, with anomalous responses centered on cultural sources (residential homes, outbuildings, and

farming equipment). Changes in topography from north to south of the site are primarily the result of changes in thickness of a sandy topsoil (overburden) which forms a steep slope splitting the north and south halves of the survey site. An undocumented report from the resident of the central home (brown roof) estimates the depth to bedrock to approximately 6.1 m beneath the foundations of his home. There is little magnetic variation observed across the steep slope where the depth to bedrock varies from 6.1 m at the edge of the northern plateau to 2.1 m in the low lying flood plain to the south. The low, uniform magnetic susceptibility of the limestone is probably responsible for this overall lack of magnetic variation.

The operation of the UGV does have a visible impact on the TMI scatter plot, especially at the transitions of magnetic classification from one colour to the next. The blurring of the transition boundary is a result of the magnetic oscillation generated by the Husky wheels as it travels. It is more pronounced when the Husky travels at high speed (as in the eastern portion of Figure 29 (bottom)) as the spatial resolution is reduced at speed. This artefact might prove detrimental to determining an accurate position of magnetic boundaries and anomalous responses.

The fourth difference noise analysis found a noise level of approximately ± 0.1 nT for the walking survey, ± 0.6 nT for the Husky UGV at half-speed, and ± 4.0 nT for the Husky UGV full speed (Figure 30). The common reference line is representative of flat gentle terrain encountered by the UGV within the survey area, in difficult terrain such as slopes, or over rocks and obstacles, the noise level was found to be ± 4.0 nT at half-speed and ± 8.0 nT at full speed. By subtracting the amplitude of the ± 0.1 nT wheel

noise determined by laboratory testing (Figure 21), the mechanical noise generated by the UGV during full-speed operations was found to range between ± 3.9 nT in gentle terrain to ± 7.9 nT in rough terrain. In first approximation, noise levels increase by one order of magnitude between walking survey and the half-speed UGV survey, and by another order of magnitude between half and full-speed UGV surveying. Surveying over difficult terrain increases the noise level by a factor of 2.

During survey operations it was noted that the UGV operating at full speed was subject to significantly more vibration and shaking of the aluminum sensor tower than while travelling at half-speed. The mechanical forces acting upon the UGV and sensor are in large part due to a lack of suspension which, at low speeds, is not as severe as the rubber wheels are able to absorb the lesser shock at the ground-wheel interface. The frequency responses of the Husky during survey operations (Figure 31) were different than those measured in controlled laboratory conditions (Figure 22). The spectra generated at 0.4 m/s and 1.0 m/s display spikes related to the periodicity of the steel wheels as they rotate. The field data, however, also shows an increased magnitude across the entire frequency range, but especially in the 2-5 Hz frequency range. As previously noted, the Husky UGV travelling at a full-speed was noted to experience higher mechanical forces acting upon the tower and sensor, which corresponds to a 7-10 dB magnitude increase between 2-5 Hz, compared to when travelling at the slower 0.4 m/s speed. For comparison, the walking survey frequency spectrum showed a magnitude of 15 dB less over the 2-5 Hz range. During the walking survey, the sensor was subjected to much less mechanical vibrations and oscillations due to the natural

suspension of the human operator progressing at a steady gait. A summary of the three surveys is listed in Table 13.

Table 13: Comparative results between UGV and human walking magnetic surveys at the Hay Bay survey site.

Parameter	Walking	Husky UGV Full-Speed	Husky UGV Half-speed
Survey Speed (m/s)	1.1	1.0	0.4
Surveyed Distance (production m)	2531	1679	1237
Survey Duration (min)	50	38	50
Productivity (line m / h)	3037	2651	1484
Spatial Resolution (m)	0.11	0.10	0.04
Magnetometer-UGV Separation (cm)	N/A	121	121
Magnetometer Height (cm)	160	160	160
Maximum TMI Recorded (nT)	57810	53640	53990
Minimum TMI Recorded (nT)	51330	51910	52641

3.6 Summary and Concluding Remarks

The Husky UGV was designed for rapid scientific prototyping applications. When applied to magnetic surveying, it was found to have a large magnetic signature associated with ferromagnetic components in the electric motors and drive train. When the motors are connected to current a TMI gradient of 2500 nT/m at a height of 33cm is detected along the x-axis of the UGV. The TMI is also subject to oscillations of ± 7 nT

during active rotation of the chassis wheels, and a fourth difference noise level of up to ± 8 nT during field surveying.

Testing the integrated UGV-magnetometer system has identified 2 hardware improvements which can be made to reduce the impact of ferromagnetic UGV components on the magnetic signal. The first improvement should be replacement of the ferromagnetic steel wheel rims with a non-magnetic composite, aluminum, or plastic alternative which would reduce the amplitude of magnetic oscillations by 84%. This is the highest priority UGV modification that would have the greatest impact on signal quality, at a low material cost (est. \$500). It is also simple to implement. The second hardware improvement should be a redesign of the sensor tower using a rigid composite. A rigid tower would be capable of supporting an increased sensor separation distance of 150 cm or higher while a customized composite could mitigate mechanical vibrations transmitted to the sensor. Beyond these hardware modifications, further attenuation of magnetic noise could be achieved by applying a compensation to the data in post-processing as is common practice in airborne geomagnetic surveying (Leliak, 1961; Groom et al., 2004). Detailed compensation strategies could also be developed to track individual wheel odometry, position and orientation of magnetic components, and used to compensate for variations in TMI due to orientation of the wheel, axles, and electric motors during survey operations (Forrester, 2011; Forrester et al., 2014). Alternately, simpler signal processing strategies such as applying a moving average filter (Versteeg et al., 2007) or a Hilbert transform (Green & Stanley, 1975) could be applied to attenuate coherent noise in the magnetic signal.

The Husky UGV was successfully integrated with the GSMP 35U magnetometer with the design and application of an aluminum sensor tower 121 cm in height. The sensor tower was able to mitigate 84% of the interference generated by the UGV systems at this separation distance. The integrated system was reliable during field surveys and generated magnetic datasets at an effective sampling frequency of 10 Hz and a spatial resolution of 0.1 m or better. The integrated Husky UGV was initially deployed on a small survey in flat terrain on the Carleton University campus. During that initial survey the position of a known cultural target was successfully identified by the detection of a magnetic anomaly generating a 625 nT response, and was consistent with results from a previous survey completed with the Kapvik micro-rover. A following survey at Hay Bay, ON, was also successfully completed which demonstrated a robust system operation in realistic field conditions. While operating at a full-speed of 1.0 m/s the robotic UGV system production was found to be comparable to the productivity of a human walking survey (Table 13).

With baseline results acquired for the Husky UGV instrumented with a magnetometer there are the opportunities to expand the applications of this integrated robotic system in the near future. One factor which limits current operations is the lack of remote operation capabilities. By integrating navigational sensors such as a panoramic video camera and a radio communications relay, the UGV could be remotely piloted by a human teleoperator from a distant base station. This would enable analogue missions in hazardous environments such as mine tailings ponds, UXO contaminated terrain, and regions of active volcanism. Alternately the autonomous

features of the UGV could be expanded to incorporate real-time TMI data into path planning for simultaneous localization and mapping (SLAM) algorithms. This could enable an UGV equipped with a magnetometer to autonomously seek out regions with pre-defined magnetic parameters, follow magnetic gradient field lines, or determine the position of subsurface magnetic features.

Conclusions

4.1 Summary

This thesis addressed the challenges of instrumenting two robotic UGVs with a sensitive light-weight potassium vapour magnetometer. UGVs have an inherent magnetic signature due to their robotic composition which must be determined in order to mitigate interference effects on the recorded magnetic signal.

The primary method employed in this study to attenuate the level of noise generated by operation of the UGV systems was to employ a boom or tower to distance the magnetometer from magnetically noisy components. A secondary method to identify specific magnetically noisy UGV components was also successfully used to develop targeted strategies which were applied to either remove the component or identify the magnitude of its impact on TMI. On the Kapvik micro-rover this approach resulted in the removal of soil sampling bins containing permanent magnets; for the Husky UGV the chassis wheel rims were identified as generating significant magnetic oscillations and are slated for replacement in the future.

For both UGVs studied, the magnetometer-UGV separation was 121 cm but noise levels, assessed using the fourth difference method, were different by two orders of magnitude: the Kapvik micro-rover generated a noise envelope of ± 0.04 nT whereas the Husky UGV generated an envelope of ± 3.94 nT. The low level of magnetic noise of

Kapvik was attributed to its very low speed (0.02 m/s) in combination with the stability afforded by a rocker-bogie suspension. In contrast, the Husky UGV is equipped with no suspension, travels 20 times faster (1.0 m/s), which causes higher levels of vibration and mechanical noise.

The two integrated UGV systems were successfully deployed on a series of robotic mapping surveys. The first two surveys were conducted over a near subsurface cultural target situated on the Carleton University campus (Table 9). The position of the cultural feature, a storm sewer, was clearly defined as a 650 nT peak-to-peak anomaly on the data acquired by the Kapvik micro-rover. The same target was later surveyed with the Husky UGV which detected an anomalous response of 625 nT at the same position. The Kapvik micro-rover data was generated at an exceptionally high spatial resolution of 0.002 m per sample. It took the Kapvik micro-rover, however, 225 minutes to acquire 135 line metres of data. Its slow speed was found to be a limiting factor for terrestrial survey applications. The Husky UGV, despite being a magnetically noisier robotic platform, performed well in surveys of both urban and natural environments. During the Hay Bay magnetic mapping surveys the Husky UGV operating at full speed generated comparable productivity values to the human operated survey of the same property (Table 13). While operating in gentle terrain and open field conditions a human operator is able to travel faster than the Husky UGV, however in rural field conditions such as deep mud or while climbing steep inclines the robotic performance of the Husky UGV is consistent at full speed while the human operator or UGV pilot had difficulty

maintaining pace. The Husky UGV has definite potential for use as a magnetic mapping platform in niche applications.

4.2 Future Work

The research performed in this survey focused on exploring hardware based solutions to reduce the impact of robotic systems on the magnetic signal of an instrumented UGV. By reducing noise due to hardware more of the signal from subsurface sources can be preserved. Alternately, modern software offers many solutions which can be applied to filter and improve the analysis of a noisy signal. The magnetic signature of the UGV systems may be characterized in detail and used to guide compensation algorithms (Forrester et al., 2014). Additional information may also be derived from a comparison of the two UGV configurations by modelling the response due to sensor elevation with respect to a common target. Finally, magnetic mapping methodology using tele-operated UGVs can benefit from improved autonomy by using real-time magnetic readings to guide pathing (Phelps et al., 2014). A mapping mission would benefit from onboard algorithms and sufficient processing power to allow the rover to survey with some degree of autonomy (Castano et al., 2007; Woods et al., 2009; Gallant et al., 2013). To maximize opportunity for science, algorithms could be developed to guide UGV navigation to survey in the direction corresponding to the highest spatial gradient of the magnetic field, along magnetic contours, or in a predefined pattern after locating anomalous magnetic features of interest.

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