Explainable and Trustworthy Robotic Aeromagnetic Data Collection and Interpretation

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Abstract—**Aeromagnetic data are essential for characterizing the subsurface of the earth and other planetary bodies. But time in the air, or in orbit, is expensive. An intelligent system would minimize the costs of collecting both regional moderate resolution and targeted high-resolution data with a single survey. (Phelps et al, 2014; Manjanna et al, 2016).** *To enable intelligent system surveys, scientists need to trust that these systems can collect, process, and interpret aeromagnetic data, as well as validate and explain the actions and results throughout the exploration process. This kind of modernized survey would improve data quality, but there is a need to maintain trust in the exploration process. The challenge, therefore, is to build these capabilities into a robotic system given the constraints of a modernized aeromagnetic survey, and to deliver explanations that the scientists using the robots can understand. We identify areas where technologies are needed to ensure trust in autonomous aeromagnetic survey.*

Keywords- aeromagnetic; airborne magnetometry; payload-directed; UAV; UAS; trust; trust related behavior

I. Introduction

A number of natural science problems depend on constraining subsurface geology and hydrology,, including earthquakes, groundwater, solute and contaminant transport, and mineral and petroleum resource estimation. Subsurface discontinuities caused by faults and changes in rock type control both fluid migration and resource boundaries. Aeromagnetic data offers one of the few ways to image these subsurface rock discontinuities, where vertical to sub-vertical contrasts in rock magnetic properties yield gradients in the magnetic field (measured on an approximate horizontal plane). Surveys typically collect data using a space-filling approach, often by bustrophedonic (lawnmower) lines spaced a few hundred meters apart to study magnetic source bodies a few hundred meters to tens of kilometers in length, although much more targeted (and much more expensive) surveys are used when more information about the subsurface is known. This surveying method has been in use for decades and uses standard data collection and processing techniques vetted over the years, and is therefore well-established and trusted by the scientific community.

II. Aeromagnetic Surveying in the Present Day

Aeromagnetic surveying has not changed appreciably since the 1950's. Aircraft carry high-precision magnetometers, and after appropriate modifications and modeling to minimize the magnetic signature of the aircraft and the sensor itself,, lawnmower lines are flown, with altitude and spacing optimized to image anticipated subsurface targets (Hamoudi et al, 2011). Approximately 10% of the lines are flown perpendicular to the rest, with crossover locations used to make minor leveling corrections in the data. No adjustments can be made during the survey to modify or enhance data collection, so the survey parameters – location, direction, altitude, and resolution – remain fixed.

The leveled, processed line data is generally interpolated to a regular grid, where the data are filtered to highlight gradients for analysis. Gradient properties, such as curvature and spatial continuity, and spatial coincidence with features on auxiliary datasets such as geologic maps, provide the basis for interpretation of the subsurface.

Aeromagnetic data collection and processing relies on a large body of knowledge, from instrument engineering to signal processing. Standard methods are well defined (Hamoudi et al, 2011), and are therefore trusted by the scientific community. Data interpretation is performed by the scientist, and is therefore trusted because it is his or her own work.

Data collection is typically performed under contract using standard procedures (fig. 1), and is not interpreted by the scientist until days to weeks after the survey. This delay in interpretation, and lack of ability to adjust survey parameters, does not make efficient use of field-deployed instrument time, and ultimately limits the investigative scope of the survey. There is a need for autonomous aeromagnetic surveys that can modify survey parameters on-the-fly to identify and image regions of interest for targeted investigation, without needing a "human in the loop" to process and interpret data.

Identify applicable sponsor/s here.

III. Next-Generation Aeromagnetic Surveys

In our vision of the modern autonomous aeromagnetic survey, robots will close the feedback loop around data collection, processing, and basic interpretation, recognizing potential targets of interest, through to the design and execution of follow-up modifications to the flight path. The building blocks of this approach have been developed in Marchant and Ramos (2014), Manjanna et al. (2016), and Salman (2018). In an autonomous survey, the location, direction, altitude, and resolution of the data are variable and dependent upon results of the robotic decisions and analyses. Such a survey enhances single-survey data collection capabilities by providing on-the-fly interpretation and targeting of features of interest, significantly increasing resolution in focus areas and increasing the overall efficiency of the survey. However, to be accepted by the community, it is not sufficient to optimize trajectories – the users need to trust the decisions of the autonomous robotic surveyor.

Figure 1. Conventional UAV aeromagnetic survey flying near the Boulder Magnetic Observatory outside of Boulder, CO.

IV. Trusting Autonomous Aeromagnetic Surveys

There are at least two levels of trust required to gain acceptance among the earth-science community: instrument and vehicle health, and decisions related to changes in survey parameters.

The first level of trust is in the instrument and vehicle health. Through self-assessment, the UAV should to be able to convey instrument health, identify abnormal instrument readings, and request user assistance if necessary. Such actions will increase a user’s belief in the competence and predictability of the UAV.

As the survey progresses and instrument systems are deemed healthy, the data will be analyzed on-the-fly by the robot. Features of interest will be identified and survey decisions made accordingly.

The second level of trust involves the motivations for behavior (modifying survey parameters), which should be communicated in a human-interpretable manner. Gradient analytics, subsequent feature identification, and decision responses to these features, are new on-board functions to be performed by algorithms rather than via human interpretation. These functions and results need to be effectively communicated to the supervising scientist for trust in the survey to be established. Supervising scientists will think in terms of map and graph interpretation; therefore high-level robotic interpretations should be communicated via similar maps and graphs. A “white box” approach is imperative: users will need transparency into the robotic decision making, with the ability to inspect lower-level decisions as interest indicates. Decisions that focus on interpreted high-value targets should also be translated into natural language. For example, if a discovered feature is found to be a local best fit for an a-priori model based on Hausdorff distance, this could be translated into “Model 1 is a best fit to the newly discovered Feature A; changing survey design to increase detail of Feature A, then explore the next area where Model 1 predicts another feature of interest.”

The lack of human interpretable explanations of behavior is a major gap in the adoption of autonomous aeromagnetic surveys by the geologic community, and currently impedes research towards maximizing the efficiency and breadth of data collection efforts. Through future collaboration we hope to engineer autonomous aeromagnetic surveys that communicate on-the-fly decisions to scientists via trustworthy language: identifying and exploring new geologic features, and the geologic models their discovery implies.

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