TRANSMITTING LIFE DETECTION DATA GATHERED BY AN EXOPLANETARY MOBILE SYSTEM

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ABSTRACT

This paper discusses development of a life detection system that performs field experiments in an exoplanetary environment and transmits measurements from a prototype Mars rover to a remote base station. Oxygen, carbon dioxide, and methane sensors allow the system to gather atmospheric data, while a multi-pixel photon counter scans soil samples to determine if there are traces of adenosine triphosphate. The integrated system processes quantitative data from the experiments using a 32-bit microcontroller and transmits the information from the rover to the remote base station through a MIMO communication system. The communication system consists of a pair of circularly polarized omnidirectional antennas and two linearly polarized Yagi-Uda antennas at the base station. The data is graphically displayed so operators can quickly determine if the samples contain extant, extinct, or no signs of life.

INTRODUCTION

Since 2012, the Missouri University of Science and Technology Mars Rover Design Team (MRDT) has been developing a mars rover prototype and currently the team has developed 8 iterations. With each rover there are many projects that require a multidisciplinary approach - especially the system developed for the 2020 The University Rover Challenge(URC) Science Mission. The design for the life-detection system was researched and devised by students studying chemistry, biology, and geology, but its practical application necessitated extensive electrical and mechanical expertise.

The URC requirements state that “Using the science package on-board the rover, teams should be able to determine the absence or presence of life, either extinct or extant, for designated samples.” Further, the teams may not bring samples back to the basestation for human-conducted testing, may not remove or alter rock samples, and may not contaminate the sample sites with on-rover equipment or with material from other sites [1]. To accomplish this task, MRDT devised a system that would test for the presence of certain gases in the air near the samples, collect and perform chemical tests on the samples, transmit video feedback to the rover operators, and provide graphical representations of the collected data. The combination of various methods allowed the operators to obtain a better understanding of the inaccessible environment..

Figure 1: Icarus Running a Simulation

DESIGN

Sensors

The science system hosts an assortment of sensors that collect different pieces of information. The methane (CH_4) sensor is capable of sampling the concentration of methane in the atmosphere every twenty seconds, with a typical current draw of 0.6 mA. Furthermore, the sensor has a sensitivity of 10 mV for every one percent change in methane concentration$_4$ with a zero drift of 0.1%v/v per month, meaning that the data the sensor produces will be relatively accurate over time [2]. To detect oxygen molecules, the sensor uses a photodiode to identify the reduction in the fluorescence that passes through the molecules exhibited by an embedded LED. As oxygen molecules pass through the sensor, they absorb the light which results in less fluorescence. The sensor is able to handle barometric pressures ranging from 500 to 1200 mbar at a maximum flow rate of one litre per minute [3]. Finally, a carbon dioxide sensor was implemented in the system. This instrument utilizes gold plated optics and exploits the principle of non-dispersive infrared

(NDIR) absorption and has an accuracy of three to five percent of the reading the sensor collects [4].

Multi-Pixel Photon Counter

The multi-pixel photon counter (MPPC), also known as a SiPM (silicon photomultipliers) consists of multiple Geiger mode avalanche photodiode pixels. It was implemented to determine how much light the bioluminescence assay expelled. This device has a peak sensitivity wavelength of 450 nm, as well as having a photon detection efficiency of 50% [5]. During initial testing of the MPPC, the team discovered that any external light caused the accuracy of the measurement to decrease. To reduce the effects of excess light, the mechanical subteam were tasked with constructing a containment unit that would reduce any excess light to reach the sensor. The team was able to detect variations in light levels, as shown in Figure 2, but were unable to optimize testing with the bioluminescence assay due to the schools response to the COVID-19 pandemic.

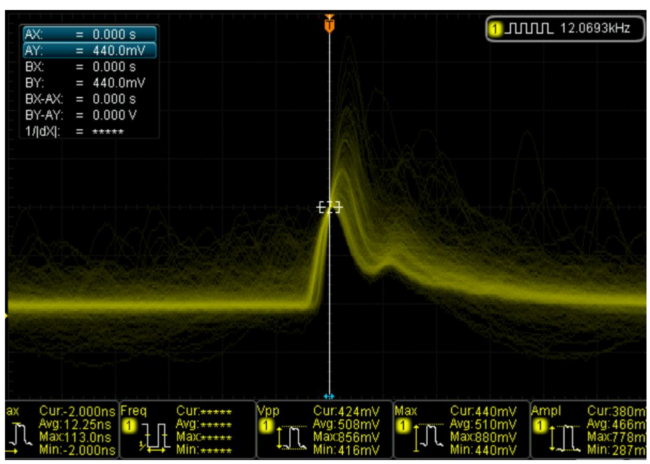

Figure 2: MPPC Testing

Microcontroller

The team's prototype science system uses two identical microcontrollers to allow for data collection and actuation. The controller features a 120 MHz, 32-bit RISC microprocessor and has a Floating-Point Unit that follows the IEEE 754 standard [6]. The microprocessor core provides several physical GPIO blocks allowing for a vast amount of GPIOs, dedicated UART, I2C, SPI, and ADC channels with 12-bit precision. Storage of custom-developed software is possible due to 1024 KB of flash memory, while rapid memory access is facilitated by 256 KB of single-cycle SRAM, which uses four 32-bit wide interleaving SRAM banks [6]. Additionally, an ethernet controller hosting an integrated media access controller (MAC) and a network physical interface operating under the IEEE 802.3 standard enable data transmission to reach 10 to 100 Mbps [6]. With these features the team is able to collect data and control the movement of the system quickly and accurately while out in the field.

Firmware

The purpose of the firmware is to enable the operators at the base station to quickly analyze data and create a hypothesis to determine the absence or presence of life. To ensure that the information is accurate, the team utilized the Dixon Q test, a statistical method to eliminate any outliers. The test subtracts a data point of interest with the closest and farthest data points, then divides the values as seen in (1).

Eq 1.

$$Q = \frac{X_2 - X_1}{X_n - X_1}$$

The firmware then removes any outliers detected in the data set, averages the remaining data, and performs error analysis. The information is then presented to the operators in a graphic display. This process facilitates quick analysis, which is necessary for success in the task. Furthermore, the science system employed a range of strategically-placed cameras that were managed by the base station. Operators were able to view the sample sites from several different angles, and could see the experiments occurring inside the rover. This visibility ensured that the operators could navigate to the sample sites, visually judge the soil and rock samples for notable characteristics, and determine whether the soil samples were reacting with the added chemicals.

Signals

To establish a link between the rover and the base station, the team uses two MIMO connections via four circular polarized omnidirectional antennas attached to the rover. The team uses a high-bandwidth RF link which operates in the 5.8 GHz band and has a dual linear MIMO sector antenna that spans 90 degrees vertically and horizontally as seen in Figure 3. The 5.8 GHz band allows for low-latency control during line-of-sight (LOS) situations like the Science Mission. All on-rover electronic equipment operates as an independent modular endpoint and can communicate with any other device via UDP transport. This is achieved with RoveComm, MRDT's custom publish/subscribe distributed IP protocol. The traffic of the data is then managed by a network switch on the rover and base station using a Rapid Spanning Tree Protocol, which simplifies the switching between RF links. This is critical because the rover must be able to operate in the 900 MHz band through a dual linear MIMO Yagi-Uda antenna. Icarus can also be controlled with a 2.4 GHz band through an additional omnidirectional antenna attached to the rover.

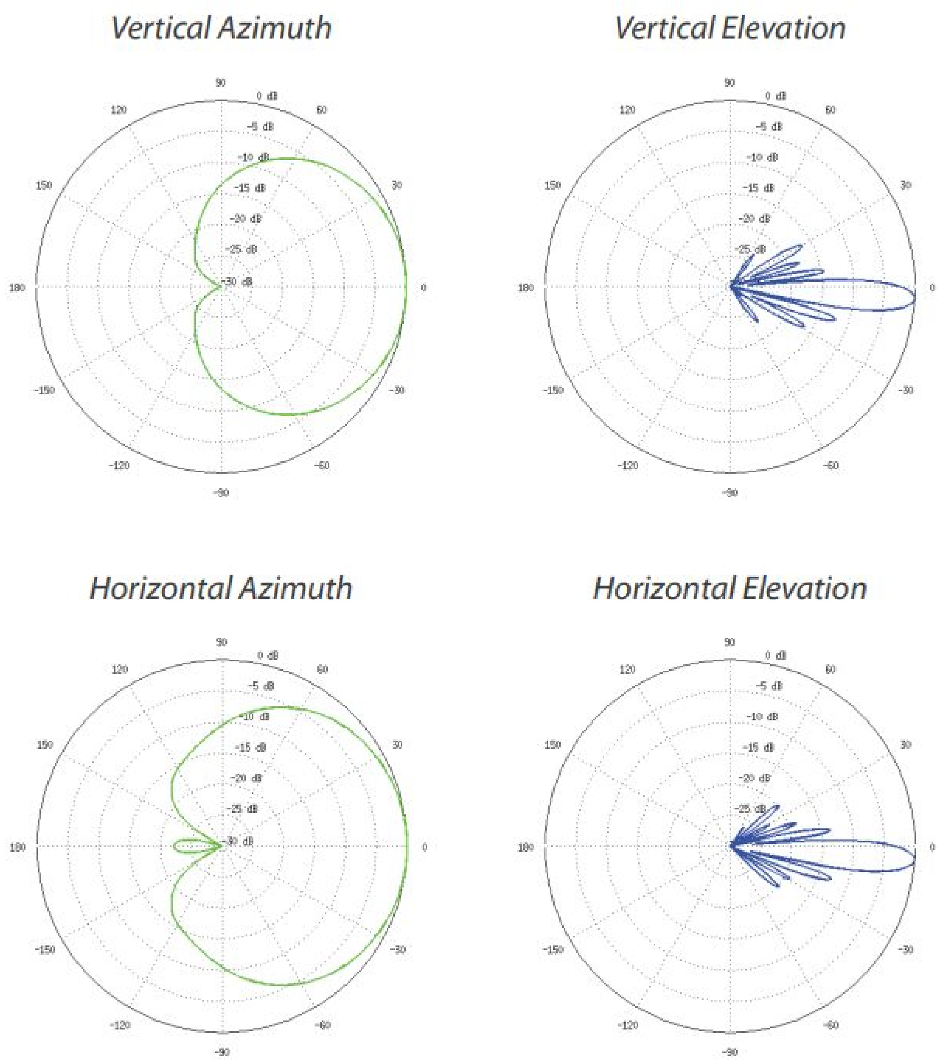

Figure 3: 5.8 GHz Antenna Radiation Patterns

DEVELOPMENT

The design of Icarus' life-detection system consists of three gas sensors, a sample collection and chemical administration system, an MPPC, an ultraviolet (UV) LED, and multiple cameras positioned at various places inside and outside the rover. The Science subteam worked with the BaseStation subteam to develop software that provides real-time data visualization, essential to quick and accurate analysis.

The electronic gas sensors continuously monitor the concentrations of methane, carbon dioxide, and oxygen near the sample sites. This data is then statistically analyzed to remove outliers and determine whether any of the sample sites exhibit significant variations from the control (the concentrations of those gases at the start line, before the rover drives to the sample sites).

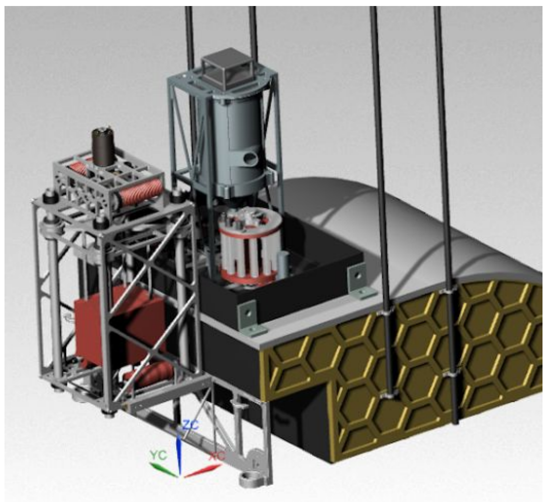

Figure 4: Icarus Science System

Soil samples are collected with a vacuum and then transported into test tubes contained within a Geneva mechanism, as seen in Figure 4. A maximum of three samples may be obtained from each site, to which reagents are then added using peristaltic pumps. The tests chosen by the team are the Sudan III test and a modified (ATP) bioluminescence assay. Cameras positioned near the test tubes are monitored by team members at the base station for reactions induced by the Sudan III reagent, which would indicate the presence of lipids. A Multi-Pixel Photon Counter (MPPC) measures the amount of light emitted by the addition of either a standard solution of firefly luciferase and D-luciferin or both a cell lysing agent and the standard solution - the comparison of these reactions will enable the team to determine whether intracellular or extracellular ATP are present in the samples. Further testing was planned to improve and optimize the system, but the COVID-19 pandemic halted all progress on the project and forced several components that would have been completed by URC to remain unfinished.

APPLICATIONS

Gas sensor data is used to determine both habitability and whether a disequilibrium of gases exists at any of the sample sites. The investigated compounds (CO_2, CH_4, and O_2) are all essential to terrestrial life and are byproducts of respiration. CO_2 is one of the main products of aerobic respiration and is a reactant in photosynthesis. Additionally, it is utilized by methanogens (methane-producing microorganisms) to create CH_4; thus, a distinct lack of CO_2 in conjunction with high amounts of CH_4 could indicate the presence of life. CH_4 is an extremely common biological waste product, and is not readily found in chemical disequilibrium with O_2 unless some process - life - is actively adding methane to the atmosphere. O_2 is also a strong bioindicator due to its lack of abiotic sources and because it is necessary for most forms of terrestrial life to survive [7].

The purpose of the Sudan III test is to determine whether each sample site contains lipids, which are essential to biological processes [8]. Distilled water and ethanol will be added to a retrieved sample to isolate lipids. Triton X-100 and Sudan III are added for cell lysis and lipid detection, respectively. A red-stained portion at the top of the sample would indicate a positive result, while a sample with light red coloring throughout signifies there are no lipids to which the Sudan III can bind [9].

The bioluminescence assay is able to detect intracellular and extracellular adenosine triphosphate (ATP) with recombinant firefly luciferase and D-luciferin. ATP is the primary storage form of biochemical energy and is required for many metabolic processes [10]. ATP is very complex, making abiotic synthesis unlikely, and is ubiquitous to terrestrial life [11]. The amount of photons detected by the MPPC is directly proportional to the quantity of ATP present [12]. Because the first reaction (consisting only of the standard solution) only involves extracellular ATP, and the second (involving both a cell lysing agent and the standard solution) involves both extracellular and intracellular ATP, MRDT can conclude that the site contains extant life if the second ATP measurement is significantly greater. If the second measurement is not greater, extinct life is possible. If no ATP is found in either sample, then no life is present.

Red fluorescence of the samples under longwave UV light indicates that calcite, a mineral often produced by biological deposition, may be present in the samples [13, 14]. This would suggest that extinct life is likely present.

Further development of the system may include incorporation of a heater and/or a centrifuge to enable a broader range of chemical tests, building a rock and mineral database to aid in material identification, and integrating spectroscopy into the system.

CONCLUSION

Although progress on the life detection system was arrested due to the COVID-19 pandemic, the research and experimentation conducted during the 2019-2020 academic year will be instrumental in improving and innovating this aspect of the rover. The team plans to design and manufacture a new, more advanced system to compete in and succeed at URC 2021.

ACKNOWLEDGEMENTS

The authors would like to thank the MRDT science team of Missouri University of Science and Technology for their contributions to this project.

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