Utilizing Wireless Meshing Sensors for Structural Health Monitoring

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ABSTRACT

To facilitate the long-range wide area in situ analyte monitoring of a subterranean structure, the US Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) has developed a robotics system, the Subterranean Probe for Locating Intrusions, Natural Threats, and Environmental Reconnaissance (SPLINTER), and a sensor agnostic wireless sensor network, the Guardian Node (GN). In support of USACE Missions, there is a need to determine the presence of harmful chemicals before humans enter the area. The SPLINTER is a common robotics system (individual), CRS(I), robot with a sensor payload that enables the robot to perform simultaneous localization and mapping (SLAM) of subterranean systems. This capability allows the robot to create a detailed map of the environment, which is then used to inform the placement of GNs. The GN is a developed in-house sensor node that forms a wireless, meshing, and self-healing ad-hoc sensor network that interfaces with ERDC-developed chemical sensing platforms such as the Army Corps of Engineers Potentiostat (ACEstat), and the in-development quartz crystal microbalance with dissipation (QCM-D) system, as well as commercial off-the-shelf (COTS) systems that utilize standard digital protocols including SPI, I^2C, and UART. Together, the SPLINTER deploys the GNs, which then enable a subject matter expert (SME) to perform near real-time analyte monitoring of a subterranean structure.

INTRODUCTION

Digimesh and other meshing topologies facilitate reliable multi-path propagation, supporting long-range sensor communication for applications like disaster relief [1] and agent monitoring [2]. These use cases demonstrate how wireless mesh networks extend the standoff range of sensing networks to allow in situ monitoring in different environments. The need for reliable, low-cost, wireless, disposable sensing platforms exists for many government and civilian applications for the continuous monitoring of places such as rivers and lakes to monitor water quality. This system can be used to monitor naviga-

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ble waterways during dredging operations to measure the total suspended solids released for specific analytes that could interfere with operations downstream. In addition to water monitoring, it can be used to detect the presence of harmful analytes in air using a sensing platform such as the Army Corps of Engineers Potentiostat (ACEstat) and relay the information to an operator.

Providing end users with a small, robust, and easy to deploy wireless meshing sensor interface fulfills the needs of continuous and semi-continuous monitoring. The proposed solution, Guardian Node, provides the capability of interfacing with multiple sensor types that communicates with other nodes within the network. By integrating data from multiple nodes, users are provided with information such as atmospheric conditions and the detection of analytes of interest over time in a relatively large area. The Guardian Node combines an STM32L5 Arm Cortex-M33 micro-controller with a self-healing wireless mesh transceiver from Digi International to enable a platform capable of interfacing with a large array of commercial off-the-shelf (COTS) systems with serial interfaces such as SPI, I^2C, and UART. In addition, the system has ADC channels available for measuring analog output systems and generic GPIO channels for custom needs.

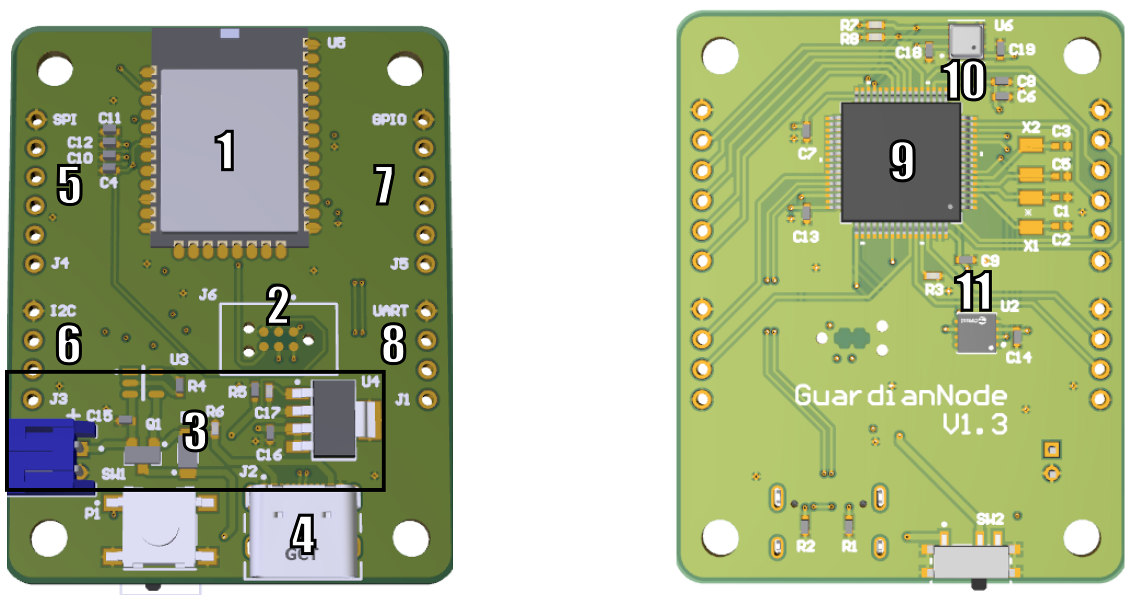
The work presented here showcases the technology being developed towards facilitating long range analyte detection through the use of electrochemistry, and COTS systems.

GUARDIAN NODE

HARDWARE

The Guardian Node offers meshing capabilities for sensors designed to transmit their output over SPI, I^2C, GPIO, and UART I/O connections. The Guardian Node features a DigiMesh XBee wireless module for mesh network functionality, STM32L5 microprocessor for I/O processing, 8Mbit FRAM for extra onboard memory, and an integrated BME680 module to provide essential environmental data independently of other sensors. Coupling multiple sensor types allows for the use of multiple detection methods for analytes of interest, and multiple I/O connections allow for a wide array of COTS sensors to be used with the nodes. The board is designed to be integrated into a deployable package, facilitating versatile field deployment with the necessary sensor modules for specific tasks. An example of a possible deployment package is shown in Fig. 1 where an older revision of the Guardian Node is coupled with a 1900 mAh rechargeable li-ion and a 2.4 GHz omnidirectional antenna from Taoglas [3]. This antenna boasts a ground-coupled antenna design that is suitable for devices where there is minimal clearance between the PCB and the antenna. Individual nodes can be reprogrammed and recharged using a standard USB-C connection while the Xbee radios are configured over the air through Digi's XCTU software.

Figure 1. Guardian Node V1.2 with Deployable Package



(a) Top

(b) Bottom

Figure 2. Guardian Node V1.3

Fig. 2 shows the layout of the Guardian Node V1.3 PCB, measuring 1.9 in. x 1.5 in. Numbers are placed within the figure to highlight specific areas of the board with a description of each number following.

1. Digi XBee RR PRO, 2.4 GHz, DigiMesh version [4]

2. Tag-Connect TC2030 serial wire debug (SWO) programming port [5]

3. Power management

    - A li-ion or li-poly battery provides power through a two pin JST PH connector. The battery is managed by the MCP73831 IC [6], and the voltage is regulated down to 3.3 V through an LP3874 IC [7]. This differs from the

V1.2 shown in Fig.1 where the voltage regulator did not facilitate a sufficiently low voltage to power the system using the li-ion battery

4. USB-C connection that can power the Guardian Node, charge the battery through the MCP73831, and provide wired data communications
5. SPI connection for external sensors
6. I^2C connection for external sensors
7. Five generic GPIO pins and a ground that can be reconfigured as ADC inputs for external sensors
8. UART Connection for external sensors
9. STM32L552RET6 STM32 microprocessor [8]
   - The firmware uses SPI to communicate with the onboard flash memory.
   - The firmware uses I^2C to communicate with the BME680.
   - The firmware uses UART to communicate with the Digi Xbee RR module
10. BME680 Temperature, Humidity, Pressure, and Gas Sensor [9]
11. CY15B108QI-20LPXI 8Mbit 20MHz FRAM [10]

The Guardian Node's mission space requires a low cost for the total materials that allows for the node and sensor to be left behind in the field without the need for recovery. Often, sensors used for monitoring are placed in inhospitable areas where retrieval is difficult or impossible. It is expected that these sensors will be left behind once the mission is complete. These sensors remain in a low-powered sleep state and only test the environment when triggered by a coordinating node within the mesh to wake the system up. While in a full working state, the system on average draws 37 mA and increases to 60 mA while transceiving data. These measurements were gathered by monitoring the power through the JST PH battery input and utilizing XCTU to perform transmissions between neighboring nodes.

SOFTWARE

The firmware of the STM32L552RET6 manages communication between the Digi module and the sensor payload, ensuring that limited bandwidth and power are used effectively. Electrochemistry-based measurements such as CV, where current measurements are made while sweeping the potential across a selected range, often produce more data than can be effectively sent in a single low-level DigiMesh packet. This necessitates data to be broken up into chunks that can be more reliably delivered. The Guardian Node firmware sends out periodic updates over the mesh network for simple sensor data that can be fit into a single chunk, such as temperature or analog voltage readings, and is also able to receive and fulfill requests for more data-intensive tasks such as CV via the mesh network. When requests for data are received from the mesh network, the STM32L552RET6 will perform the analysis and store data locally and then divide the resulting data into chunks which can then be sent to the requesting node. The requesting node can then check that all chunks have been received, and request any that are missing. A graphical management front-end, shown in Fig. 3, allows the end user to view and manage node status within the sensor mesh, as well as send requests for data from tests with large data outputs from one or more nodes simultaneously. The request will then be fulfilled and data returned to the front-end for user download and analysis. The front-end performs the active checks needed to ensure that all data has been received and missing data is requested by the front-end to be resent by the STM32L552RET6 firmware.

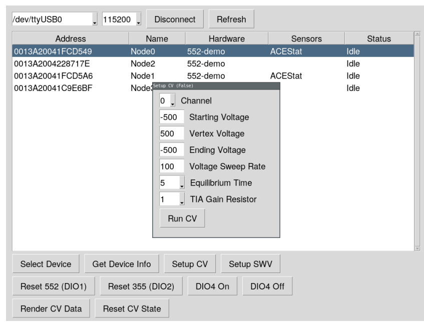


Figure 3. Graphical Management Front-end

PRESSURE SENSOR TEST

To test the capabilities of the Guardian Node, we conducted a proof of concept experiment using an acrylic tube and the Keller PA-25Y pressure sensor. The sensor requires 10 V for operation and gives an output voltage of 0 to 5 V to measure a span of -0.3 to 0.3 bar with an initial offset of about 2.5 V representing 0 bar. We measured the water pressure at three different heights to see how much change would occur by using 3.5 cups of water. In order to read the measurements, the GN used convergence equations, shown in Fig. 4, to translate the bar measurements into inches of water. The initial reading of the pressure was about 5.2 in with a voltage of 2.6 V and current draw of about 3 mA. We filled the tube up with 3 and 5 inches of water to see what the total water pressure and voltage change would be.

```
float keller_pressure_remove_offset(float voltage) {
    return voltage - scaleoffset;
}
float keller_pressure_voltage_to_bar(float voltage) {
   return voltage * scalefactor;
}
float convert_bar_to_inwater(float bar){
    return bar*bar_to_inwater_scalefactor;
}
```

(a) Conversion Equations

```
float scaleoffset = 2.502f;
float scalefactor = 0.12f;
float bar_to_inwater_scalefactor = 401.865f;
```

(b) Scale Factors

Figure 4. Converting Functions

RESULTS

We observed an overall water pressure change of 5 inches with minimum voltage loss and the results of our experiment can be seen in Table I. This was what we expected to happen despite some external factors such as excess noise and thermal drift not being excluded from the testing. A real world use case of this could be in the form of a sleep wake system for deployable sensor mode. The system would wake the GN for about a minute every 5 minutes to record a pressure reading and go back to sleep in order to conserve power. Overall, our experiment was successful and is one of the few ways the Guardian Node could assist with structural health monitoring needs.

TABLE I. EXPERIMENT RESULTS

Point	Inches of H2O	Voltage
Initial 0 in	5.256896493	2.695580946
3 in	7.952477439	2.0571813
5 in	10.00965874	4.752762247
Ending 0 in	5.080984167	4.928674573

FUTURE WORK

The next steps on this project outside of continued testing and iterating of the Guardian Node involve better interfacing with existing sensing hardware and automation of analyte detection through machine learning. Features that allow for a wide variety of sensor packages must be balanced with portability that facilitates remote placement. Additional efforts will be made in optimizing the QCM-D board package to facilitate more stable sensing and sensor placement.

For better interfacing, the ACEstat is currently being reduced to a small form factor with castellated edge connectors for direct coupling with a motherboard that would also house the Guardian Node. Many of the features within ACEstat have been reduced to a minimum while not compromising results. This interconnection allows for a more secure deployment, thus reducing the likelihood of a node dying in the field.

CONCLUDING REMARKS

To meet the needs of the nation, ERDC developed a small form factor, disposable, wireless sensing system for the detection of analytes of interest. Using an STM32L5 microprocessor with a DigiMesh enabled wireless transceiver, a self-healing mesh network is created to extend the detection stand-off and allow sensing in inhospitable environments. The Guardian Node can be coupled with other ERDC developed technologies such as the ACEstat or any sensors that provide standard serial interfaces or analog output. These nodes are expected to be irretrievable following mission completion.

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