Utilizing Sprouts WSN Platform for Equipment Detection and Localization in Harsh Environments

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Abstract— This paper discusses the application of our Wireless Sensor Network platform called Sprouts, to monitor the steel shovel-teeth on shovelling equipment used in oil sands mining operations in Ft. McMurray, Alberta, Canada. If a fallen shovel-tooth reaches the rock crushers, serious damage to the crusher gears is expected. The Sprouts platform is utilized to monitor the viability of the shovel-teeth on the shovel bucket's teeth adapter. In addition, if a shovel-tooth becomes detached, Sprouts is used to estimate its location. By utilizing our Sprouts plug-and-play protocol, we implement a magnetic field and ultrasound distance sensor modules to detect the event of a fallen shovel-tooth. In addition, a wireless power transfer unit and two supplementary antennas are embedded in each shovel-tooth to aid in localizing (using trilateration) the part before it reaches the crusher.

Keywords- Wireless Sensor Network; Sensor Platform; Shovel teeth; Ground Engaging Tools; Oil Sands; Mining; Localization; Trilateration

I. INTRODUCTION

Wireless Sensor Networks (WSNs) provide a practical solution for fine granularity event detection in a wide scope of application domains. Wireless sensor nodes are useful event reporting candidates in applications where wired sensors cannot be deployed. In addition, they provide a low cost and ultra-low power sensing solution with little user intervention. Therefore, we have designed Sprouts as a field deployable WSN platform specifically suitable for harsh environments, Sprouts is a rugged, low power, cost effective, modular, open-source and multi-standard WSN platform. The small carbon footprint of Sprouts nodes, in addition to their rugged metallic enclosure, allows for seamless deployment in harsh industrial environments such as Oil Sands mining. Sprouts sensor nodes (SNs) adopt modular architectures that allow new sensor modules (SMs) to be automatically detected and remotely configured. In such mining industry, excavation shovel-teeth detachment poses a huge challenge to the crushing stage of mining the oil sands. The shovel-teeth are the first to engage the hard rock surface, thus, susceptible to constant erosion, breakage, and detachment. The shovel-tooth (shown in Fig. 1) usually falls within two to three days of digging operation. We deploy Sprouts SNs on top of the shovel and inside the shovel-teeth to detect the detachment and falling of the teeth.

Sprouts nodes provide a solution to: real time detection of the fallen teeth, wireless communication while buried under the rocks and oil sand, accommodating wireless communication with minimal modification to the teeth structure, optimize power consumption due to the small power supply of the sensing nodes. Moreover, the harsh operational environment, constant impacts, and constant vibration require a resilient and rugged sensor platform. Therefore, we propose a system with two objectives. The first is optimizing system accessibility to detect shovel-teeth detachment through redundant sensing mechanisms. The second objective is designing a reliable localization mechanism to find fallen teeth in order to facilitate fast retrieval before reaching the crusher stage. Meeting these objectives is the aim of the Sprouts platform which will ensure a rugged system that facilitates real-time monitoring of shovel-teeth and endures the harsh conditions in which it is deployed.

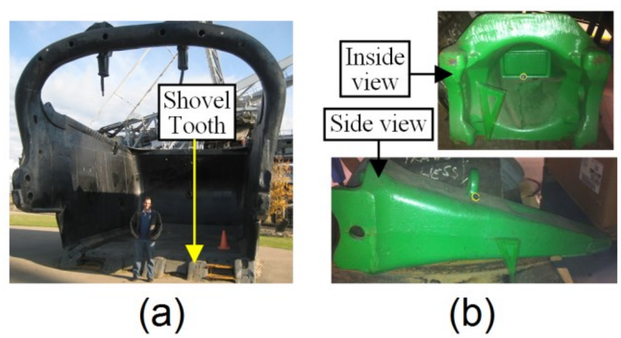

Figure 1 Oil Sands shoveling operation equipment: A. Shovel bucket B. Newly manufactured shovel-tooth

The paper is organized as follows: Section II discusses the background of the application and problem description of the shovel-teeth monitoring. Section III describes the architecture of Sprouts WSN platform and its unique features. Section IV describes the method of detecting and retrieving fallen shovel-teeth. Section V discusses related work and the paper is concluded in Section VI.

II. BACKGROUND AND RELATED WORK

Oil production from Oil-Sands is a long process that begins with shoveling the oil-impregnated sand found within layers of rock in preparation to crush it. Excavation shovels are utilized 24 hours, year round, to collect the oil sand. The shovel bucket (shown in Fig. 1) comprises of shovel-teeth, adapters, and the

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mounting body. Due to the continuous impact of the shovel-teeth with the rock, teeth will break off in a few days due to such strong impacts.

When a shovel-tooth is detached from its adapter, several severe problems may occur. First, the shovel-adapter is exposed to possible permanent damage that prevents proper attachment of a new shovel-tooth. Second, the fallen shovel-tooth could puncture very expensive truck tires, which only few companies in the world produce. In addition, a broken shovel-tooth may get shoveled with the load and make its way into the crusher where serious damage to the oil production train occurs.

Due to the above challenges, automated and immediate notification and localization of the broken shovel-teeth is of utmost importance to the Oil Sands operators. However, in the field, bad weather conditions and environmental hazards limit the inspection and involvement from technicians. In addition, sensors cannot be attached to the outside of the shovel-tooth because of frequent impacts and constant erosion.

III. SPROUTS PLATFORM

Sprouts is a WSN platform that utilizes sensor nodes (SN) to collect data from sensor modules (SM) and report them to the sink node (coordinator). Sprouts coordinator transfers the collected data to backend server for further data processing and visualization. The main components of Sprouts platform are shown in Fig. 2. The main features of the Sprouts platform are its modular, ultra-low power, rugged, and plug-and-play capabilities. Each SN can be customized using external SMs as seen in Fig. 3. With its rugged SN, Sprouts provides an optimal solution for monitoring industrial equipment within harsh environments. The small footprint along with the metallic enclosure enables the platform to fit within the monitored system and to withstand harsh environmental elements (e.g., shock, vibration, high temperature, impact).

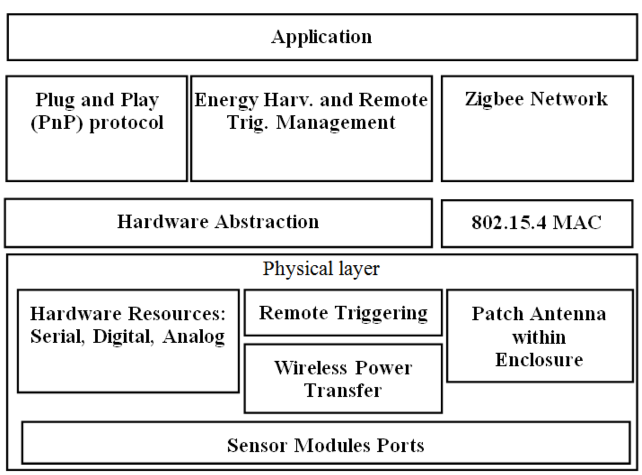

Figure 2 Sprouts platform components

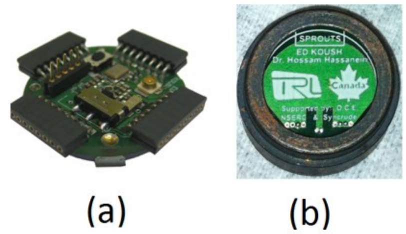

Figure 3 Sprouts SN: (a) Four PnP bus ports (bottom view). (b) External metallic enclosure

The Sprouts platform comprises of three components: the middleware, the SN, and the SM. SN and SM are the entities that are deployed in the field for monitoring shovel-teeth.

A. *Sprouts middleware*

Sprouts middleware architecture is based on the DREAMS architecture [9], which is our middleware architecture approach towards remotely reconfigurable and upgradable software modules. The DREAMS architecture is a unique energy-harvesting aware middleware composed of interchangeable software modules. DREAMS architecture simplifies middleware architecture implementation complexity, decreases faults associated with low energy sources, and increases design flexibility associated with remote upgrades for energy-harvesting WSNs. In [9], we discuss how DREAMS is uniquely different from other middleware approaches for energy-harvesting WSNs. Furthermore, the module-based middleware architecture of DREAMS lends itself towards an intuitive method of programming i.e. a graphical-based environment similar to that of LabView.

B. *Sensor nodes*

The hardware architecture of Sprouts SN comprises of an external PnP modular interface, which allows the user to implement custom SMs for specific applications. PnP is enabled by four SM ports. Each SM port provides a customization channel to configure the Sprouts platform for a given application. For networking, Sprouts adopted a standard Zigbee network for its mesh network topology support and varied use across a broad range of applications. Each of the SNs have an Energy harvesting capability that is implemented to monitor energy levels and control wireless power transfer (WPT), remote wake up trigger, and can recharge a backup battery when excessive harvested energy is available.

The antenna of Sprouts SNs is the most susceptible component of the platform to the outside harsh environmental factors. In particular, corrosion, electrical shock, and physical damage can irreversibly damage the antenna. Therefore we utilize a novel miniature tapered trapezoidal patch antenna, which is also used as an enclosure cover (as shown in Fig. 3-b and Fig. 4), thus, serving two purposes.

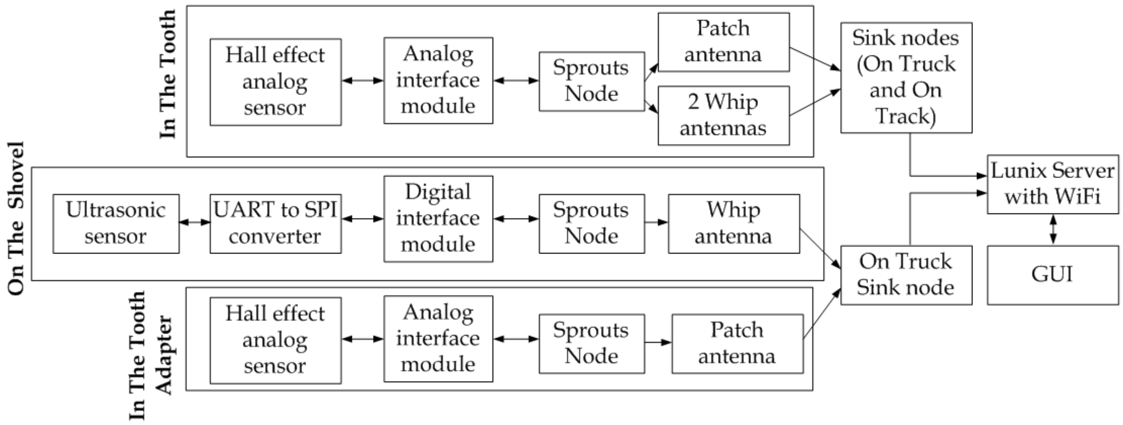

Figure 1 Detachment detection system consists of three components

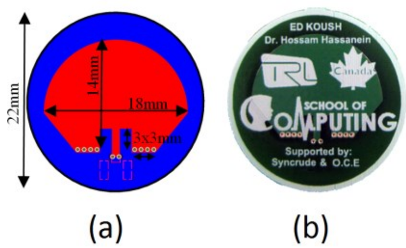

Figure 5 Patch antenna design and implementation using Altium Designer (a) Altium Designer copper layout (b) Fabrication result

C. Sensing module

In order to customize Sprouts for a broad range of applications, we designed a PnP protocol which accepts externally attached custom modules, which we refer to as Sensor Modules (SMs). An SM can be a generic or an application dependent device, compliant with Sprouts PnP protocol, and may include one or more senor elements (SEs). Sprouts PnP protocol is established between Sprouts and attached SMs in order to achieve a high level of customization. Due to the small size of Sprouts, only four SMs can be connected at any given time. However, one SM may contain multiple SEs, thus, a limit of four SMs does not pose any serious constraints. In addition, a custom SM may be designed to act as a PnP expansion module to provide more PnP ports. PnP protocol is designed for direct connection with the SN without using cable extensions, which is similar to how a microSD memory card is directly plugged into cameras or smart-phones. Therefore, the cost limitation of cables is eliminated allowing us to expand the number of connections needed to design a simple to use PnP serial communication bus.

IV. Detachment Detection

To detect fallen shovel-teeth we integrate multiple SMs to SNs. This serves both redundancy and resilience under the harsh environment, and aid in the efficiency of the system and its accuracy in detecting breakage and reporting it in real-time. Our detachment detection system consists of three components, two hall-effect sensors and one ultrasonic distance sensor (as shown in Fig. 5). On the shovel itself, ultrasonic distance sensors (UDS) are mounted which monitor the availability of shovel-teeth. USS is connected to a SM that is programmed to collect information from the UDS and report the information to the SN. In the shovel-teeth adaptor, a magnetic field sensor is embedded inside the adapter body to sense the availability of shovel-teeth. Similarly, another magnetic field sensor is embedded in shovel-teeth to sense the availability of the adaptor.

The enclosure of the embedded SNs is ruggedized to protect the node's components against harsh environmental factors. The enclosure is an integral part of the SN when dealing with harsh environments. We used a cylindrical copper enclosure to protect the node against oxidation. Upon completely encapsulating the platform within the metallic enclosure, we fill the inside of the enclosure with translucent epoxy compound, MG-Chemicals-832C [5]. The combination of the epoxy encapsulation and the copper enclosure provides the platform with a structure that is extremely tough against shock and vibration, water and humidity proof, and temperature tolerant.

A. Magnetic Field Sensor

Magnetic field sensors are embedded in both, shovel-teeth and adaptor as shown in Fig. 6-a. This sensing mechanism capitalizes on an important aspect in the design of the shovel-tooth capped on the shovel-adaptors, namely the quasi-constant distance between them. That is, after each shovel-tooth is mounted on an adaptor, it maintains a given distance while in operation; this continues until its breakage as it falls off. The SM is based on a magnetic field sensor that senses the magnetic field from a magnet that is mounted on the other side (the shovel-tooth or the adaptor). The distance between the shovel-teeth and adaptor is less than 2cm in the configuration shown in Fig. 6-a. Once the shovel-tooth is detached, the magnetic field sensor detects a field that is below a predetermined threshold (as will be explained shortly) and the SM triggers the SN to transmit alarm packets to the coordinator at the truck cabin. The alarm packets are translated into an audible and/or visual alarm displayed to the operator. Simultaneously, the packets are routed by the coordinators to the main server to be filtered and visualized on the PDA's of the monitoring personnel.

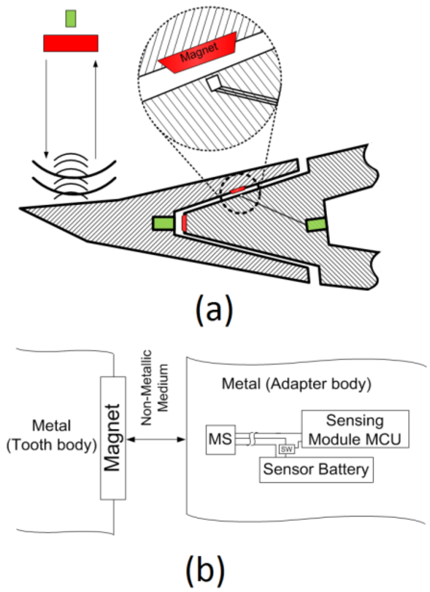

Figure 6 (a) Magnetic field sensor and SN placement in the shovel-teeth and its adaptor. (b) Connection configuration of magnetic sensor to the module.

The connection from the magnetic sensor to the SM is illustrated in Fig.6-b. The MS is an analog sensor that is based on bipolar junction transistor; hence, the power consumption is high. To sustain the sensing operation for a period that surpasses the expected shovel-tooth lifetime, the magnetic field sensor is switched "ON" by the SM for one second every 30 seconds. We used round (2.5cm diameter) magnets with a magnetic field of 1.08 Tesla. The sensing element is a linear hall-effect magnetic position sensor [5]. To define the detachment threshold at which the SM triggers the SN, the round magnet is moved from 1cm to 8cm from the MS (the output voltage[1] vs. distance from magnet to magnetic field sensor is plotted in Fig.7). Since the distance in between the shovel-tooth and the adapter is less than 2cm, the detachment threshold is defined as two volts.

[1] The supply voltage is 3.6V

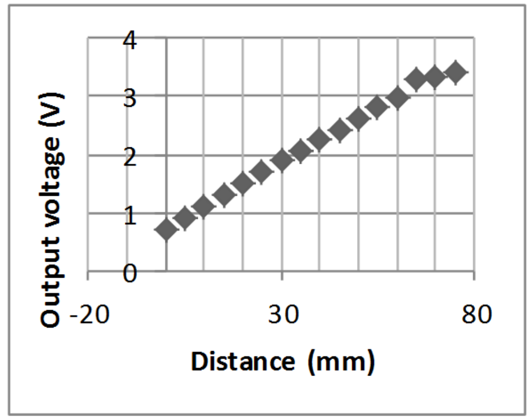

Figure 7 Output voltage from MS when the magnet is moved from 1cm to 8cm

B. *Ultrasonic distance sensor*

A redundant method for monitoring the availability of the shovel-teeth is established through an ultrasonic distance sensor (UDS). The UDS uses ultrasound signals generated by a piezoelectric transducer (PZT) to monitor the shovel-teeth. The sensors are mounted on the shovel body and connected to multiple SNs as shown in Fig. 8-a. The SNs report distance readings from UDSs to the coordinator inside the excavation shovel cabin. Each USD sensor monitors one shovel-tooth, however, the obtained distance is reported to multiple SNs at once. UDS is connected one "primary" SM in each SN (the darker (red) SM in Fig. 8-b). In addition, it is connected to "secondary" SM in the other SNs (denoted by the yellow SM in Fig. 8-b). The connection to multiple SNs provides communication redundancy when one SN is out of power or has lost its communication with the coordinator (as seen in Fig. 8-b).

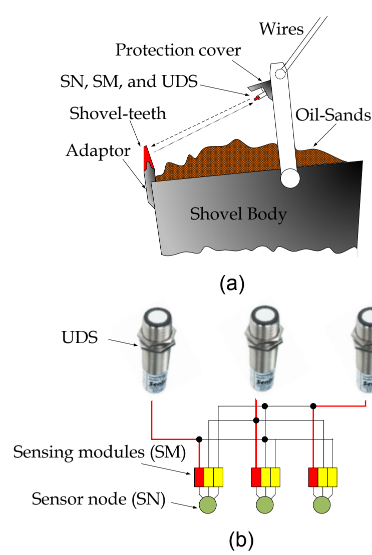

Figure 8 (a) PnP ultrasonic distance sensor placement and (b) connection configuration

The UDS is connected to the SM via the Serial Peripheral Interface (SPI) of MSP430 microcontroller. The microcontroller initializes the UDS and requests the distance information once every 15 seconds. This is due to the lower power limitations in SN with UDS when compared to SN inside shovel-teeth or adaptors.

An overview of the UDS is depicted in Fig. 9. Ultrasound waves emitted from the UDS, travel through the air until they hit the tip of the shovel-tooth, in which it is reflected back to the UDS piezoelectric transducer. The piezoelectric transducer generates a weak electrical signal upon receiving the reflected ultrasound wave, which is then passed to the ultrasound receiver through a multiplexer (MX). The ultrasound receiver is composed of a series of band pass filters (BPFs), low noise amplifier (LNA), power amplifier (PA), detector (DET), low pass filter (LPF), and a comparator (CMP). The CMP transforms the received ultrasound signal into a digital form that is sent to the microcontroller in the SM via SPI.

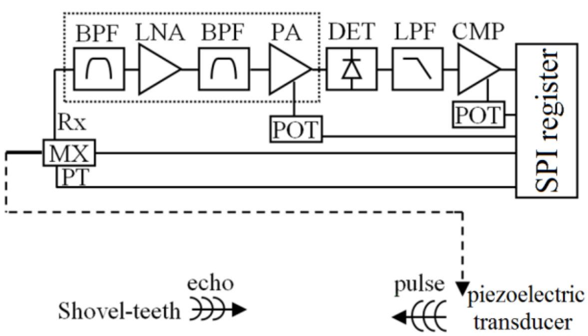

Figure 9 Ultrasound distance sensor components and operation concept overview

Given the harsh nature of industrial environments, fault tolerance is also considered throughout the software and network architectures. Error recovery functions from software failures on the source node are addressed by reinitializing specific hardware components, software resets, watchdog timers, voltage level monitoring, and a backup memory containing original firmware.

V. Localization

In addition to the magnetic field sensor, the SN in the shovel-tooth is equipped by wireless power transfer (WPT) circuit and two supplementary antennas. These additional components assist in retrieving the shovel-tooth from the field to prevent it from damaging the truck or reaching the crusher. Hence, we utilize sink nodes positioning on a selected number of trucks and gates in the field.

In addition, Sprouts utilizes an RFID-like wireless power transfer using a pair of schottky diodes HSMS-2852 for RF-to-DC energy harvesting. This method of energy harvesting does not increase the physical size of the platform in comparison to other methods such as solar-power or vibration-based energy harvesting. A remote radio triggering is achieved by combining the HSMS-2852 with an ultra-low power (0.4μA) comparator LTC1540. The remote triggering system works with a minimum input power of -32 dBm radio signal power. Another great advantage of using the LTC1540 is the ability to create an ultra-low power addressing scheme. Using ASK demodulation signal received by the comparator, Sprouts can receive a 4200bps UART baud rate from the interrogator, or smart-phone, to determine whether the SN needs to enable the RF radio to receive packets. The combined RF remote trigger and UART receiver is shown in Fig. 10. The benefits of such capability are utilized in Section V.

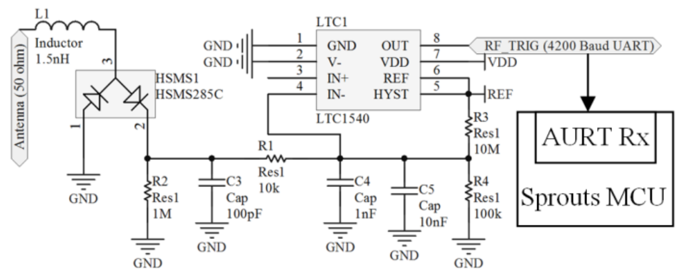

Figure 10 Ultra low power RF remote trigger and UART receiver

The supplementary antennas are independent and multiplexed by an RF switch with asynchronous transmission as shown in Figure 7. Two of the antennas (noted as supplementary antennas) are probed into the shovel-tooth and covered with industry rated epoxy. The purpose of the two antennas is to reduce directionality dependency that will increase both detection and localization accuracy.

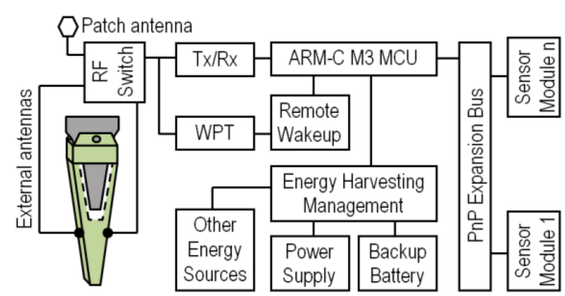

Figure 11 Sprouts platform hardware architecture showing two additional external antennas used for localization

In order to communicate with the embedded Sprouts nodes in the fallen shovel-teeth, multiple locations potentiate a higher chance of communication with Sink nodes. Sink nodes are equipped with high gain antennas, and the resources to compute and store large amounts of information. To facilitate a higher detection probability, two types of sink nodes are considered for deployment. The first type is mounted on the top of trucks (mobile sink nodes), hence labeled cabin sink nodes. They have the opportunity to initiate communication with a fallen shovel-tooth, as it will be in its near vicinity when one falls off. Accordingly, sink nodes encompass the following main components:

1. High directivity gain antenna and a high receiver sensitivity of -110 dbm
2. A modified BLE communication protocol with remote triggering addition to the MAC
3. High speed (1.0GHz) dual core ARM processor
4. Peripherals:
    a. WiFi communication with PDA's of monitoring personnel.
    b. Alarm devices (audio, visual)
5. GPS module (to aid in estimating the fallen shovel-tooth location)
6. Unlimited local power from the shovel-truck

The second type will be location gates (fixed sink nodes) that are deployed on critical paths that most shovel-trucks take to reach the final dumping zone into the crushers. The importance of the location gates stems from the crucial detection phase prior to reaching the crushers where significant damage can occur from crushing the steel shovel-teeth. Therefore, location gates are mounted with high sensitivity antennas to detect a signal beaconed from a Sprouts node inside a fallen shovel-tooth that made its way into the load of a shovel-truck. Accordingly, all trucks at risk of having a fallen shovel-tooth in their load would have to pass through another path for shovel-tooth retrieval.

It is important to note the correlation between the received signal strength intensity (RSSI) of the received signal from a fallen shovel-tooth and its directivity 0, and the number of readers required to receive the signal. Thus, to boost reception, sink nodes are placed on trucks with a GPS receiver to act as anchors in the multilateration process for shovel-tooth localization. To localize the fallen shovel-tooth, RSSI based localizing method with multilateration is applied by the sink nodes to determine the location by adjustable power level.

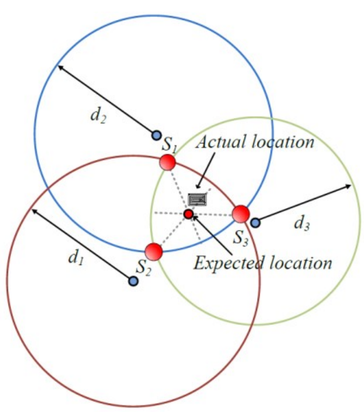

Figure 1 An example of Multilateration technique with three sink nodes ($S_{1,2,\text{ and }3}$) to localize a shovel-tooth.

The shovel-tooth can be localized in two dimensions when three mobile/fixed sink nodes (or more) detect its RSSI and map it to some distance value that is considered to be the radius of a circle with the sink nodes at the center, as shown in Figure 1. As the SN antennas provide three RSSI readings, the reliability of the estimation scheme is increased and the radius d is mapped to the average RSSI from these antennas. The intersection between the three circles is used to estimate the location of the shovel-tooth.

VI. Related Work

Employing WSN to monitor the reliability of industrial machinery brings many benefits including time to failure estimation, faster damage control response, increased quality control, determining fault sources, increased production efficiency, building statistical databases of sensor reports, to name a few. The closely related work to this paper is the i-GET commercial product solution sold by Identec Solutions [5]. The i-GET is an active RFID tag that only monitors the presence of ground engaging tools (GETs). When a GET, or shovel-tooth, is broken off, the i-GET solution notifies the operator of the missing shovel-tooth. There are several differences between i-GET and our solution. Sprouts uses a modular interface to add external sensors. In addition, we use trilateration to aid in the retrieval of fallen shovel-teeth, which i-GET does not provide. In a similar industrial monitoring application [3], MICL2 nodes are used to monitor abnormal temperature changes in bearings of cold rolling mills in order to predict equipment faults. However, the MICL2 platform is relatively large in size, lacks modularity, or a wireless standard network in comparison to Sprouts. PIPENET [4], uses Intel Motes, which is based on Intel's XScale processor PXA271, and has an ARM v5 core architecture. The PXA271 is not an ultra-low power (ULP) processor for WSN, and was originally released for mobile phones. Thus, it supports scalable speeds up to 416MHz, and can run Linux. PIPENET requires a high power platform to monitor the structural integrity of bulk-water transmission pipelines by analyzing acquired data such as acoustic vibrations, fluid flow, and pressure. Sprouts platform is better suited for low data rate applications due to its limited energy reserve provided by a small rechargeable coin battery. TABLE I shows a comparison between Sprouts and other popular commercial platforms.

TABLE I. Comparison Between Sprouts and Other Platforms

Platform Name	*MCU*	*Core*	*Size (mm)*	*Network*		*Battery Power*	*Remote Wakeup*	*ULP MCU*	*Energy Harvesting*
				Radio	*w/s*[a]				
Sprouts	EFM32G 230F128	ARM v7	23x10 Cylind.	BLE nRF8001	Yes	20mm CoinBatt.	Yes	Yes	Yes
IRIS	ATmega 128	AVR 8-bit	58x32 x7	Zigbee RF230	No	2 x AA	No	Yes	No
MicaZ	ATmega 128	AVR 8 bit	58x32 x7	Zigbee CC2420	No	2 x AA	No	Yes	No
TelosB	MSP430 F1611	RISC 16bit	65x31 x6	Zigbee CC2420	No	2 x AA	No	Yes	No

SunSpot	ARM 920T	ARM v4	64x38 x25	Zigbee CC2420	No	Lith.Ion 3.7 V	No	No	No
IMote2	XScale PXA271	ARM v5	36x48 x9	Zigbee CC2420	No	3 x AA	No	No	No

a. w/s: Network stack is embedded in the radio, which does not require the MCU to implement it.

VII. CONCLUSION

In this paper we introduced a solution that utilizes our wireless sensor network platform, Sprouts, in a harsh environment application. Sprouts platform is deployed to monitor detached shovel-teeth on equipment used in the oil sands mining operations in Ft. McMurray, Alberta, Canada. Our platform is capable of accommodating several sensing mechanisms and being embedded inside the shovel-tooth, the adaptor, and shovel body. With its small footprint, Sprouts sensor nodes are embedded inside the shovel-tooth with minimal modification to its structure. The modular property of the Sprouts platform is not limited to the oil sand industry; in fact it is applicable for monitoring other metallic and non-metallic parts in the general mining industry.

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