ELECTROMAGNETIC ENERGY HARVESTING FOR SENSING, COMMUNICATION, AND ACTUATION

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Abstract

The harsh construction environment requires unusually robust sensing and actuation technology to make real-time pro-active safety alerts a reality. We have developed a battery-less, wireless sensing and actuation device as an option to advance pro-active safety in construction. By employing electromagnetic energy harvesting and eliminating the need for a battery, our device will function in harsh environments for many years without requiring service or maintenance. In addition to the sensing capabilities normally associated with passive RFID tags, which also employ electromagnetic energy harvesting, we have also included a piezoelectric speaker to generate and transmit audio warning signals to warn workers of dangerous situations. Ultimately, the device will be affixed to a safety hard hat, dubbed a "SmartHat" which will audibly alert a worker if an RFID reader-equipped hazard is nearby. We have developed a custom antenna design for plastic hard hats that exhibits good omni-directional performance. We will describe our "SmartHat" sensor tag in this paper along with presenting preliminary laboratory and field performance data.

KEYWORDS: Safety, Real-time, Warning and Alerts, RFID, Sensors.

INTRODUCTION

The use of RFID technology in construction applications has a long history (Jaselskis 1995). Most prior use of RFID in the construction industry has focused on tracking construction materials, tools, and equipment (Goodrum 2003, Song et al. 2004 and 2006, Grau et al. 2009) on the job site. Additional work has been done in the area of record-keeping for facilities management and equipment maintenance history (Ergen et al. 2003, 2006a and b). The precast concrete industry has focused on RFID technology as a way of handling lifetime tracking of concrete components (Pheng and Chuan 2001, Akinci et al. 2007). Recent research in sensor tags and sensor networks has focused on the integration of sensors with RFID tags, for example to deliver internal concrete strain measurement (Carkhuff and Cain 2003, Andringa et al. 2005, Song et al. 2007).

There is relatively little prior work in RFID application to construction site worker safety. In its traditional use in access control, RFID badges have long been applied to construction site access. More recently, RFID tags have been applied to fall protection harnesses (Swedberg 2006) to track who is using the harness and when it was last inspected. Recently, one of the authors has begun to work (Vogt and Teizer 2007) with a combination of RFID tags and laser scanners to determine whether pipe-fitting is being performed correctly and safely on oil rigs.

It is a common misconception that the term RFID refers to a single technology. Instead, the term RFID encompasses many different technologies under the umbrella of radio frequency identification. Perhaps the most important differentiating factor among the various RFID tagging technologies is the source of the RFID tag's operating power. There are two main types of RFID in common use today: passive RFID, where tags do not contain a battery and the tag's operating power is supplied by the reader's radio frequency energy, and active RFID, where tags contain a battery that supplies operating power for the tag. This distinction is shown in Table 1.

Table 1: Comparison of Active RFID and Passive RFID Tags

Technology	**Features**	**Applications**	**Tag Cost**
Active RFID	- Battery Powered - Range of up to 100m +	- Sensor Tags - Real time location systems	- US$5.00+ depending on memory, packaging, and sensors
Passive RFID **(This Work)**	- Battery-less: Operating power obtained from reader signal) - Low Cost - 'Unlimited' Lifetime	- Person, equipment, or asset ID - Robotic navigation - Sensor Telemetry	- US$0.07+ depending on memory, packaging, and sensors

In a passive RFID tag, there is no battery on board to supply operating power. The primary advantages of passive RFID tags are low cost, because all electronic components except the antenna can be integrated into a single integrated circuit, long lifetime, because there is no battery to run down, and immunity to harsh conditions, because widely varying operating temperature has insignificant effect on the operation of the CMOS integrated circuits.

The primary disadvantage of passive RFID is limited read range. In general, the read range of a passive RFID tag is limited by the strength of the reader's transmitted signal (Figure 1). If the reader's signal is less than that threshold, the tag will be unpowered and inert. Typical passive RFID tag read range using current UHF RFID technology and a 1-Watt RFID reader exceed 5 meters, although this figure is improving rapidly as new, more power efficient tags are developed.

In contrast, because of the presence of its battery an active RFID tag can contain an active radio transmitter, yielding a much stronger response signal from the tag (see Table 1). This has the primary advantage of very long range, as much as 100-300m in some applications. Because a battery is present in the tag, it is possible to include an optional sensor that monitors a condition such as temperature over a long period of time and telemeters stored sensor data to the reader. The primary disadvantages of active RFID tags are relatively high cost compared to passive RFID tags, and limited lifetime and limited temperature range because of the limitations of the battery used on the active RFID tag.

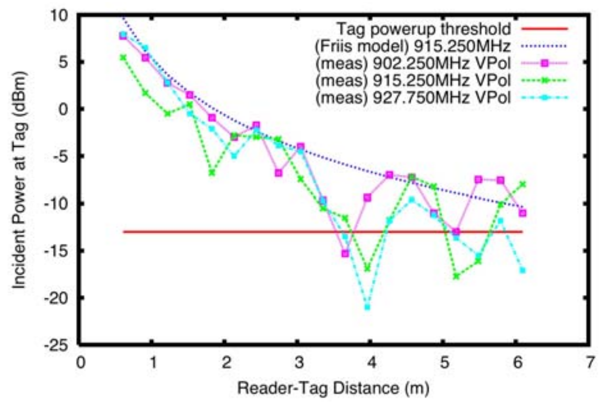

Figure 1: Received Operating Power vs. Distance for Passive Ultra-High Frequency Tag

Another factor involved in the selection of RFID technologies for construction applications is the operating frequency. As illustrated in Table 2, different operating frequencies have different properties because of the interaction between the RFID tag's electromagnetic signals and commonly used materials such as wood, metal, concrete, and liquids.

Table 2: Comparison of Different RFID Operating Frequencies

Frequency	Features	Applications	Limitations
Low Frequency 125KHz	- Mature Technology - Reads through skin - Reads through liquids and concrete	- Access Control - Embedded or implanted structural or biosensors - Cable or pipe markers	- High cost - Short read range (<1m)
High Frequency 13.56MHz	- Mature Technology - Reads through skin	- Access control, Ticketing, Mass Transit	- Moderate cost - Short read range (<1m)
Ultra-High Frequency (UHF) 860MHz-960MHz **(This Work)**	- Emerging Technology - Long Range: Passive Tags > 5m Active Tags > 100m - Fast read rates - Supports passive tags and active tags	- Logistics, Supply chain management - Real time location **- Safety warning (This Work)**	- Poor performance when embedded inside liquids, skin, or concrete

Employing Energy Harvesting in Construction Safety Applications

Our vision is to employ the unique unlimited lifetime feature of electromagnetic energy harvesting to deploy sensors that detect the proximity between a worker and a heavy machine, and to use the harvested energy to provide an audible, targeted warning to each worker who is in danger of collision with a machine. We propose to provide each worker's hard hat with a specially designed energy harvesting passive UHF RFID tag like the one shown in Figure 2. This tag will be provided in the form of a self-adhesive circuit that can easily be applied to the inside of a standard plastic hard hat. It is a particular goal that the tag's mechanical design and choice of location inside the hard hat must comply with all safety regulations. To ensure worker privacy, only randomly assigned ID numbers will be stored on the RFID tag and this number will not be associated with the worker's name at any time. The purpose of the unique ID is to discriminate between the machine operator, who is expected to be in close proximity to the machine while operating it, and any other worker who may cross paths with the machine.

If an RFID tag is damaged or becomes non-functional it will be replaced with a tag of the same ID by programming a new tag. We will equip each heavy machine with a UHF RFID reader system similar to that shown in Figure 3. We have simplified this task by previously adapting the RFID reader system to be easily mounted on machines equipped for surveying instruments by providing a standard surveying tripod mount. The RFID reader system can also be attached to the machinery with a magnetic mount that permits the reader system to be easily moved around to adapt to different types of machines.

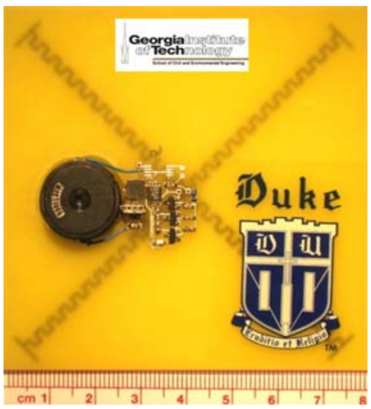

Figure 2: Energy Harvesting Passive UHF RFID Tag with Piezoelectric Actuator (10cm x 10cm)

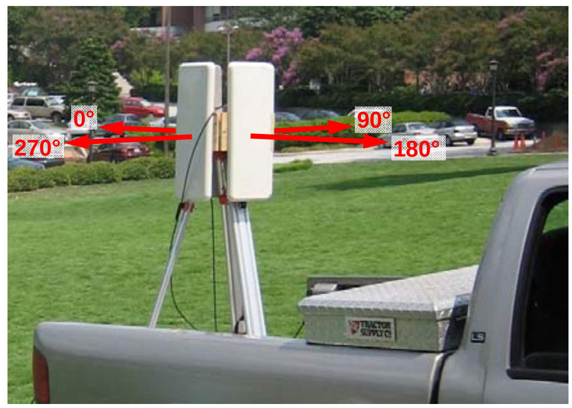

Figure 3: Preliminary RFID Reader System Mounted in Standard Pickup Truck Bed

DESIGN OF THE ENERGY HARVESTING BASED WARNING DEVICE

The primary challenge in designing a battery-less warning device is ensuring a reliable source of energy for the circuitry mounted in the worker's hard hat. There are many potential sources of energy that could be harvested in the context of a body worn device, including thermal differentials between the worker's body and the ambient temperature, direct extraction of mechanical work from the person (e.g. a shake-powered flashlight), or indirect extraction of mechanical work from the person through an inertial or vibration driven power harvester (Paradiso and Starner 2005). We have decided not to pursue inertial or vibration driven power harvesters due to unknown survivability when subjected to high g-forces experienced during even routine impacts, as when a worker bumps his head on a girder under ordinary circumstances. It is also possible to imagine the use of a solar cell mounted on top of the worker's hard hat although we have decided not to pursue this approach for three reasons (1) modifying the plastic structure of the hard hat could reduce its structural integrity (2) the exterior surfaces of the hard hat are subject to dirt and continuous small impacts that could damage the solar cell and (3) many construction tasks are performed indoors or below ground where there is little light to impinge upon the solar cells. We are also constrained by the allowable cost of the energy harvesting circuit; safety approved hard hats cost as little as US$10.00 so it is important that the added cost of the warning circuitry not exceed US$1.00-$2.00 in high volume manufacturing.

We have therefore decided to concentrate on electromagnetic energy harvesting from a transmitting source located on the construction equipment itself. A photograph of the device we have developed is shown in Figure 2, while a block diagram of the device is shown in Figure 4. The objective of the rectifier circuitry shown in Figure 4 is to extract as much energy as possible from the incident radio frequency signal transmitted by the reader mounted on the construction equipment. The objective of the energy storage capacitor is to accumulate this energy over time to accumulate enough energy to drive the piezoelectric speaker to create the warning sound when it is required. The warning device is controlled by an ultra low power microprocessor that manages the available energy and responds to proximity warning commands sent by the reader device mounted on the construction equipment. We have designed our piezoelectric speaker to produce a peak sound intensity level of 110dB SPL within the hard hat to enable a worker to easily hear the sound of the warning even when wearing ear protection. If the worker is not wearing ear protection the warning sound is not likely to cause lasting hearing damage during a warning scenario. In our opinion it is most important to prevent a worker-machine collision which could prove fatal.

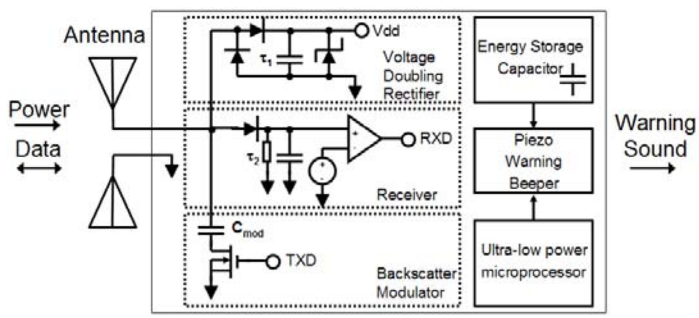

Figure 4: Block Diagram of the Energy Harvesting Based Warning Device

Antenna and Electromagnetic Energy Harvester Design

At the UHF frequencies employed in this work, power transfer from a source to an energy harvester is governed by Equation 1, which is an upper bound based on the Friis free space transmission model, as shown in Figure 1.

$$P_r = P_t - 20\log\left(\frac{4\pi d}{\lambda}\right) + G_t + G_r + L_p + 10\log\eta \qquad \text{Equation 1}$$

From Equation 1 we find P_r, the harvested power available to run the warning tag, in terms of the transmitted power P_t from the reader mounted on the construction equipment, the distance d between the worker and the equipment, the operating wavelength λ, and various antenna parameters G_t, G_r, and L_p.

Optimizing the SmartHat Antenna Design

We have determined that an average worker hard hat has an available region of approximately 10cm x 10cm x 0.3cm inside the plastic housing where the warning device could be mounted. We have developed a cross-shaped antenna (visible in Figure 2) fabricated from 1mm thick printed circuit board material that exhibits nearly omni-directional performance when mounted inside the top of the hard hat as shown in Figure 5. A traditional dipole antenna, which is the typical design for most passive RFID tags, exhibits significant nulls in its response pattern when the incoming wave is parallel to the axis of the dipole (at zero and 180° with respect to the dipole axis). This can lead to poor performance when the user's head is turned in certain directions with respect to the construction equipment. In contrast, the crossed-dipole antenna we have developed for the "Smart Hat" exhibits a much more uniform response regardless of the user's head orientation with respect to the construction equipment (see Figure 6) without the nulls exhibited by the single dipole at zero and 180°.

Figure 5: Energy Harvesting Based Warning Device Mounted in Plastic Hard Hat

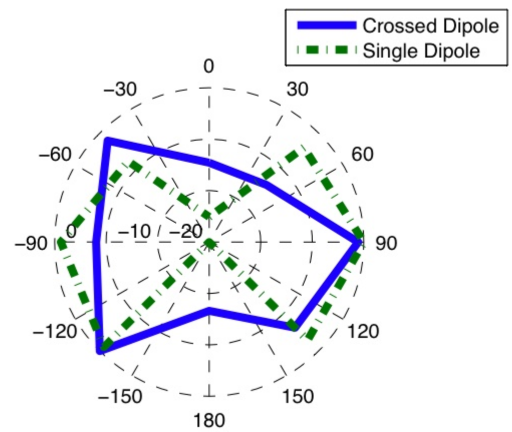

Figure 6: Measured Omni-Directional performance of the Crossed Dipole Antenna

Optimizing Energy Harvester Efficiency η

Given fixed values for the antenna parameters due to the available size and placement of the antennas both inside the hard hat and mounted on the construction equipment, we seek to maximize η which is the efficiency of the power harvesting circuit itself, in other words how much of the incident radio frequency energy from the reader unit is available as DC operating power for the tag. We have developed a series of energy harvester models using different numbers of power rectifier stages (Figure 7) using the Agilent Technologies ADS microwave simulation tools that allow us to predict in advance which circuit structures deliver the most operating power to the tag, and therefore maximize (1) the distance at which the tag harvests enough energy for operation and (2) the safety factor when operating at a given distance.

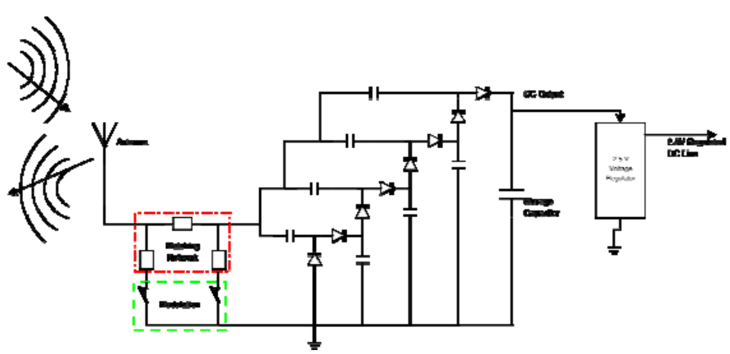

Figure 7: Circuit model of electromagnetic energy harvester (*n*-stage rectifier)

By successively running the ADS model for energy harvesters of different numbers of rectifier stages *n*, we find the optimal number of stages n_{opt} for a given application. Figure 8 shows the optimal number of energy harvesting rectifier stages given a particular operating power requirement for the SmartHat tag. We find in our application that the 4-stage rectifier configuration gives the maximum output power given the tag's minimum operating voltage of 1.8V and compare our simulation to measured results in Figure 9.

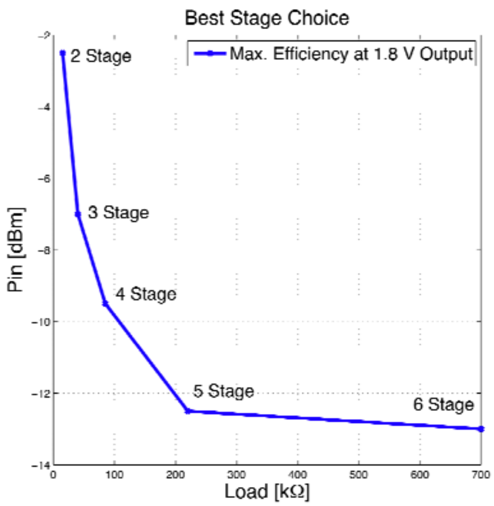

Figure 8: (Simulated) Number of rectifier stages given 1.8V operating requirement for SmartHat tag. The *n*=4 case was chosen for our final implementation.

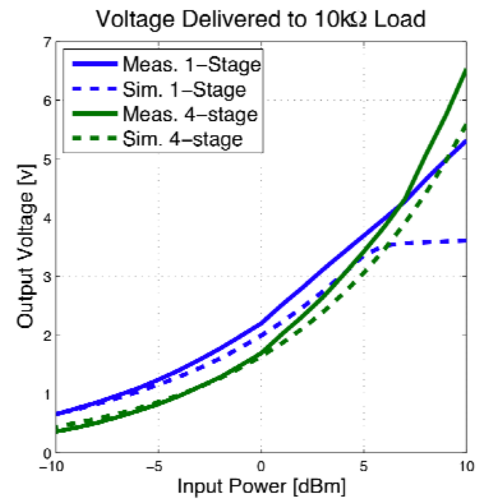

Figure 9: (Measured vs. Simulated) Achieved output voltage for given input power, *n*=1 and *n*=4 stage harvesters

We have found good agreement between our ADS simulations and the measured energy obtained from the SmartHat tag. We obtain a peak energy harvester efficiency η≈40% under the normal operating conditions for the SmartHat tag's energy harvester. This value is within a few percent of the results reported in the current literature (Sample 2008, Umeda 2005).

PRELIMINARY FIELD EVALUATION OF PASSIVE RFID

Preliminary evaluation of passive RFID concentrated on a field experiment in an open area that is similar to construction site settings which involve heavy equipment. The measurement site did not include field variation, such as radio interferences from power lines or any other obstructions that could have limited the field-of-view of the reader. It is assumed that measurements in the construction environment can produce varying results due to a number of objects being present, including materials, heavy construction equipment, existing terrain or other as-built structures. The purpose of this preliminary field experiment was to determine the read range of passive GEN2 RFID tags, including the SmartHat tag, using a commercial RFID reader and antenna system. A secondary objective was to identify a commercially available GEN 2 RFID tag that comes with long read ranges.

The measurement infrastructure included four bi-static RFID antenna panels that were mounted on a tripod on top of the bed of a pickup truck (see Figure 10). Each RFID antenna was of the same model and had a frequency range 902-928 MHz with a gain of 8 dBic (min), and a field-of-view of 70° (azimuth) and 60° (elevation). Each of the antennas was oriented in a different direction, namely 0°, 90°, 180°, and 270° (see Figure 10). The only direction that had an obstructed view was 180°, facing the cab of truck. A researcher mounted the RFID tag and SmartHat device on a construction helmet and approached the vehicle-RFID reader/antenna system from different angles. Several distance measurements were conducted for every 15° angle. At the moment the RFID tag identification number was recognized within the user interface of the RFID reader, the distance between the RFID tag and the reader was recorded using a laser distance measurement instrument (1” robotic total station). Field tests also included whether the orientation (pitch, roll, yaw) of passive RFID tags played a role in signal transmission and in responding to the signals the RFID reader antennas emitted. The research approached the antennas from the same angle multiple times. The shortest distance measurement was recorded. The impact of tag orientation was recorded.

Results to one experiment using the first prototype SmartHat tag are illustrated in Figure 10. The results show that read distances in outdoor environments of 6 m or greater are possible once the SmartHat tag is within the field-of-view of the antenna(s). Orientation of the RFID antennas had little influence on readings. Although an engineered validation of the results is pending, general experimental observations were:

- Type and field-of-view of RFID antenna played a significant role in achieving larger read distances. Omni-directional antennas can increase the RFID reader system’s field-of-view. The truck cab limited the read range in the 180° direction.
- Orientation of commercial passive GEN2 tags played a role in impinging signals.
- Signal delays between RFID tag and RFID antenna exist. A RFID tag in motion (attached to the helmet of the researcher) achieved further read distances, whereas tags in the same static position may not or only sporadically have returned a signal.
- The SmartHat and several commercially available passive RFID tags achieved read distances greater than 5 m.

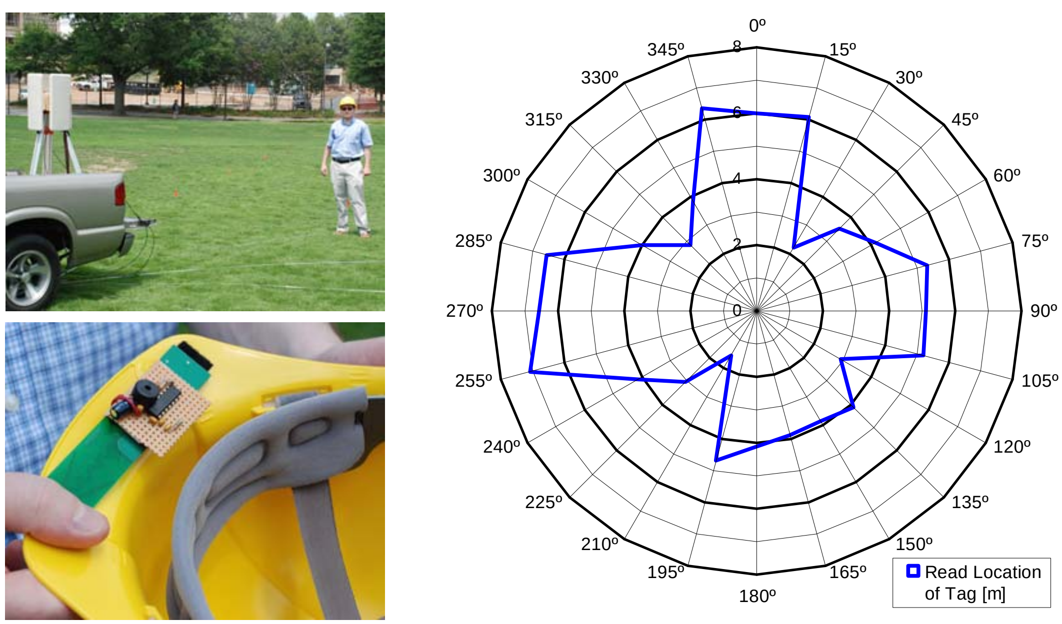

Figure 10: Preliminary results of using passive RFID / SmartHat in an open field

Since the experiments have been conducted, several advancements have been made to passive GEN2 RFID tags and the SmartHat tags. Improved performances are very likely. Further validation is necessary within the laboratory and construction environment.

CONCLUSIONS

In this paper we have presented an approach for using electromagnetic energy harvesting in a new way; in addition to the identification function provided by an ordinary passive RFID tag, we have added energy storage capability as well as actuation in the form of a warning speaker to the SmartHat tag. We have nearly completed the engineering design of the SmartHat tag and are now beginning field trials at a construction site in the Atlanta, Georgia, U.S.A., area during 2010. Future work will compare the incidence of reported "near misses" between scenarios with and without the SmartHat warning device and will continue to optimize the cost and performance of the electronics package itself. The investigation of technology adaption and human-technology interaction will be part of future research efforts. The role and effectiveness of real-time pro-active technology in safety applications will need to be evaluated to rapidly advance a group of injury prone industries. The construction industry has been belonging to this group for decades whereas other industries were able to significantly reduce their incident rates.

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