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Infrastructural Internet-of-things Using Quasi-self-powered Structural Health Monitoring Sensors

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Abstract

Current structural health monitoring (SHM) techniques focus primarily on maintenance and thus lack the ability and specificity to provide actionable information in the event of extreme/rare events or disasters like hurricanes or earthquakes. While battery-powered wireless sensors can evaluate the condition of the structure at a given instant of time, long-term operation requirements force these devices to use long-sleep cycles and hence are unable to fully quantify the extent of the damage. On the other hand, self-powered sensors can continuously monitor the structural condition without the need for any maintenance; however, the scarcity of power that can be harvested limits the range at which the sensors could be wirelessly interrogated. In this paper, we propose a quasi-self-powered sensor that combines the benefits of self-powered sensing with the benefits of battery-powered wireless transmission. By optimizing both the functionalities, a complete sensor system can be designed that can continuously operate between the structure's maintenance life-cycles and can be wirelessly interrogated at distances that obviates the need for taking the structure out-of-service. We present case studies of environments where prototypes of the quasi-self-powered sensors have been deployed, including on the Mackinac Bridge in northern Michigan.

1. Introduction

Infrastructure is vital to the prosperity of a nation, facilitating the transport of people and resources while serving as a catalyst for economic growth. However, like all things that weather the elements over long periods of time, infrastructure also experiences continuous cycles of wear and tear that effect its overall integrity. In addition to this cumulative damage, there is also a possibility that the infrastructure might experience a high-impact but rare event, such as a hurricane or earthquake. While these types of events exert massive amounts of force on the structure, they persist only for short durations relative to the deployment life of the infrastructure. Any post-disaster repair and prognostication would require detecting and recording information from these acute events during this short-duration.

A majority of current structural health monitoring modalities focus on long-term sensing to support routine maintenance procedures. These technologies use different sensing principles to detect damage in structures, such as some ground penetrating radar (Alani, Aboutalebi, and Kilic 2013) and embedded piezo wafers (Song et al. 2017). To facilitate instrumentation of an entire infrastructure, like a multi-span bridge, many research groups have proposed battery-powered wireless sensor networks (WSN) for the purpose of SHM. These WSN's are composed of a sensing modality that measures and records relevant structural parameters such as stress, acceleration or vibration (Noel et al., 2017) in addition to a wireless telemetry interface. The major benefits of this technology are their small footprint, low cost, and minimal maintenance, which allows them to be fully deployed over the structure they monitor. However, the fact that these systems are battery powered presents a significant tradeoff for the engineers. In order for the nodes to last for the lifetime of the structure, they can only wake up and sample very infrequently. This could cause them to miss vital information in determining the health of the structure if a high impact event were to occur when the node was asleep. It is evident that in order to combat this deficiency a network needs to be designed that can constantly be sense and record. Several groups have eliminated a battery by including passive Radio Frequency Identification (RFID) tags (Zhang et al., 2017), however these passive elements have a limited communication distance due to their passive nature.

To address these challenges, (Aono et al., 2016) proposed the Infrastructural Internet-of-Things (*i*-IoT) for the purpose of structural health monitoring, using a self-powered Piezo Floating-Gate (PFG) sensor (Chakrabartty, 2010) (Chakrabartty et al., 2011). The operational energy for the PFG sensor is asynchronously harvested from the sensing signal itself, as a result the sensor can continuously operate and record events without the need for extrinsic powering. In this paper, we further exploit the self-powered nature of the PFG sensor to create a quasi-self-powered WSN that incorporates PFG sensing within the context of *i*-IoT. A vision of this *i*-IoT platform for structural health monitoring can be seen above in Figure 1, where the platform will be embedded on a structure, continuously monitoring the system and recording its observations, only relaying the information back to the user when an interrogator modality is present. In the remainder of this manuscript, we will discuss the basic principles of operation of the PFG sensor core (2) and the wireless sensor node (3), finally discussing the full i-IoT deployment on the Mackinac Bridge in northern Michigan.

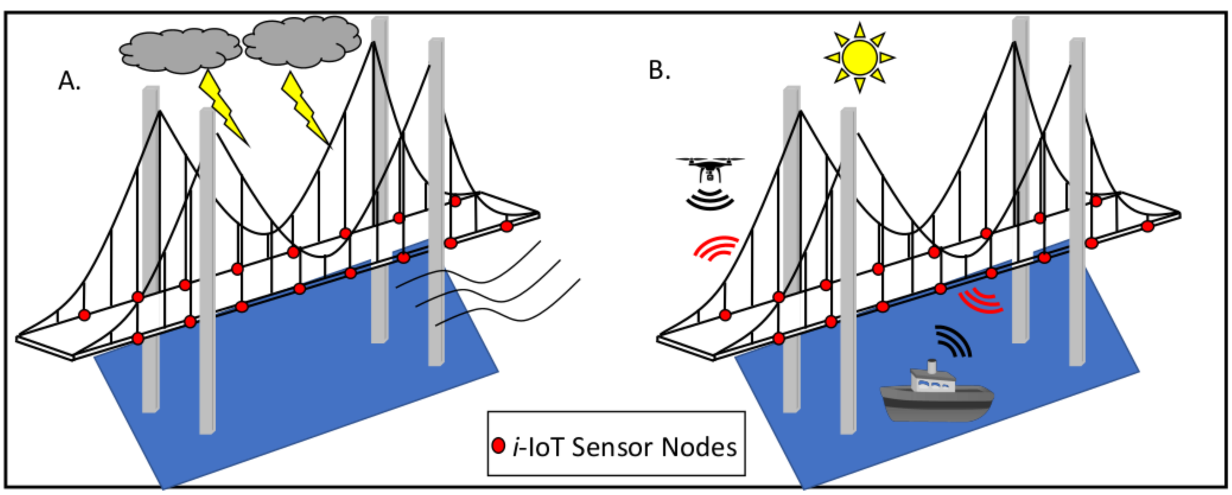

Figure 1: *A potential vision for infrastructural Internet of Things (i-IoT). In Figure 1.A, the structure outfitted with i-IoT nodes experiences a high impact event, such as a hurricane. However, despite the high forces affecting the structure, the embedded sensors are still able to collect and record throughout the event due to their event-driven detection and data recording. Figure 1.B illustrates the ability of multiple platforms to communicate with and collect data from the nodes once the acute event has ended, allowing for a determination to be made with regards to the health of the structure.*

2. Piezo Floating Gate (PFG) Sensor: Principles of Operation

The PFG Sensing Platform consists of two major components, a piezoelectric disc and the Piezo Floating-Gate Sensor core, which are used in conjunction to create a self-powered data logger for sensing and recording the strains or acceleration applied to infrastructure (Chakrabartty, 2010). This system takes advantage of several physics principles that allow for it to operate as a self-powered entirely self-powered fashion. Each of these fundamental principles will be discussed as they relate to the overall operation of the sensor and the basic operational principles of the device.

2.1 Piezoelectric Disc

A piezoelectric material is a transducer that allows for the conversion of kinetic to electrical energy (Jaffe, 2010). This transfer of energy requires no external power source to be applied, thus making it ideal to be integrated into a self-powered sensing system. The selection of the piezo dimensions and properties is very important step to ensure optimum functionality of the sensor, particularly for the data interpretation phase. Depending on the dimensions and type of the transducer, the harvested voltage can be adjusted to a specific strain level.

2.2 Piezo Floating Gate Sensor Core

The Piezo Floating Gate sensor core operates as a continuous data logger in the nanowatt power domain due to its ability to operate using the power provided by the signal that it wishes to measure. The PFG sensor cumulatively records the strains and accelerations affecting a structure through the principle of Hot Impact Ionized Electron Injection, which is the ability of electrons that flow through the channel of a Metal Oxide Semiconductor Field Effect Transistor (MOSFET) to break through the silicon-silicon dioxide barrier when a sufficient electric potential is applied across the terminals of the device. Figure 2.A provides a graphical representation of injection and the electrons ability to jump over an energy barrier. These exited electrons are then stored on an electrically isolated layer, which traps them indefinitely, which inherently allows the number of electrons stored on this gate (and the inherent potential it generates) to serve as a mechanism for the storage of information (Chakrabartty, 2010).

The current deployment version of the PFG sensor core has seven channels, each injecting at a different input threshold ranging between 8 to 12 Volts. However, when a specific channel is triggered and begins injecting, all channels with a subsequently lower injection threshold will also be triggered and inject. As multiple injection cycles occur on each channel as a result of several strain events, the cumulative history of the strains applied to the piezo is registered on the floating gates of the PFG, creating a self-powered data logger capable of registering the cumulative structural health history of a structure throughout the systems deployment (Aono et al., 2018, Aono, 2018). Using this technology, a precision of 13.3 bits has been reported using the floating gate (Huang et al., 2013). The rate of injection of each of the sensors can be modified off-chip, allowing for the user to tune the sensor for a specific task.

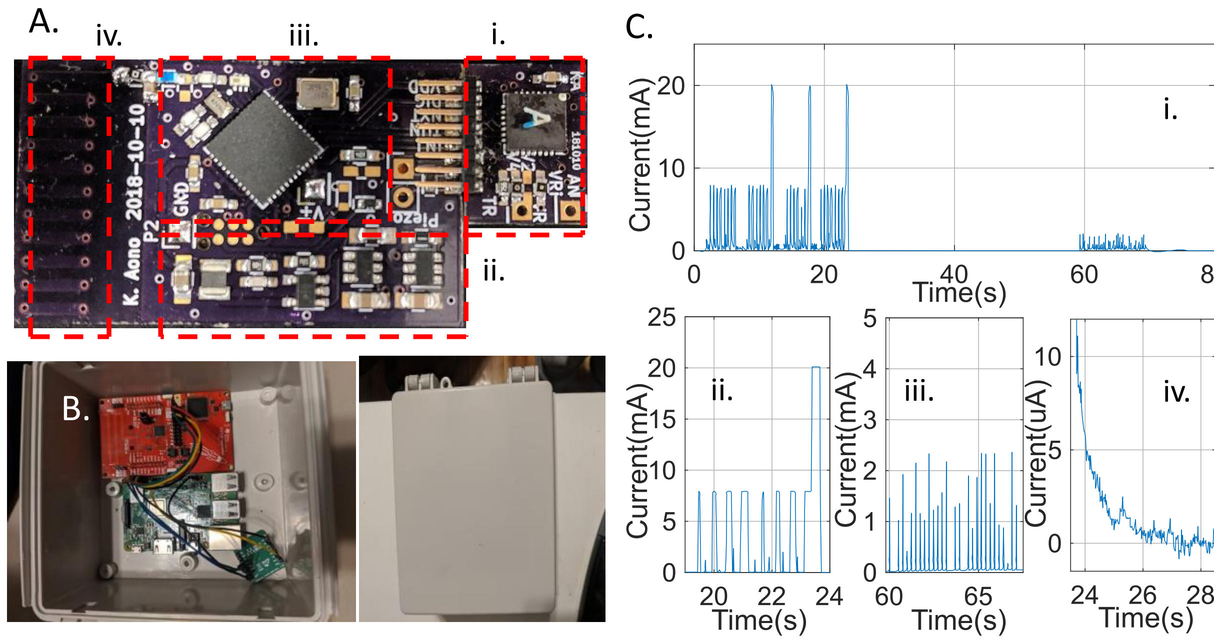

Figure 2: *A shows a prototype for the i-IoT sensor node highlighting the i) PFG sensor core, ii) timer and regulation circuitry, iii) RF MCU, and iv) antenna. B contains an image of the reader system. C contains several plots illustrating the current consumption of the i-IoT node: i) Overall current consumption over the user present and user not present wakeups, ii) zoomed in version of a wake up and transmit while the user is present, iii) zoomed in version of a wake up with no user present, and iv) the transition between the system being awake as it transitions to being asleep.*

3. Quasi-Self-Powered Wireless Sensor Node

In order to allow for the sensors to be read from while the structure is still in operation, a wireless interface has been integrated with the PFG sensor core and piezoelectric disks to create a quasi-self-powered wireless sensing system. Each sensor nodes contains a TI CC1310 Wireless Microcontroller (MCU) and has support to interface with up to three PFG sensors at once. The system has been optimized to minimize the number of transmissions that are required by only waking up and collecting data when the user is present to record data from the sensors. When the user is not present, the node operates in a deep sleep mode, where it only consumes nanoamps of current. A tunable wake-up circuit is used to change the frequency with which the sensor node wakes up and checks for the presence of a user. An image of a prototype that accommodates one PFG sensor core can be seen in Figure 2.A, while its current consumption profile can be seen in Figure 2.C. Currently, using a standard ½ AA battery (1 Ah) and transmitting only 3 times a day, our prototype has an operational lifespan of over 23 years (Aono, 2018). Note that a traditional system cannot leverage this deep sleep mode, lest it lose out on the ability to perform periodic sampling of a sensor; in the quasi-self-powered system, a self-powered sensor will continuously remain in operation, storing statistics related to the structure's health in nonvolatile memory for the actively-powered wireless telemetry system to transmit.

Several different receiver modules have been designed for the user depending on the specific requirements of the deployment. These implementations range from systems that interface with a laptop to systems that can be interfaced with drone for the collection of data from sensors in remote locations. Most recently, a system has been designed to be embedded along with the sensors that can not only record information from the PFG sensors themselves, but also record information about the environment around the sensors. This system is driven by a Raspberry Pi 3B+ (RPi), which also allows for the possibility of wirelessly interfacing the interrogator node with the Cloud, allowing for real time evaluation and interpretation of the data collected by the PFG sensor nodes. While an RPi was used for ease of prototyping, all of these features can be integrated into a microcontroller driven platform, which can be driven using a significantly smaller battery. The prototyped RPi system can be seen in Figure 2.B.

4. System Deployments

The Mackinac Bridge is the largest suspension bridge in North America, connecting the upper and lower peninsulas or Michigan and spanning almost 5 miles. In the spring of 2017, a portion of the bridge was instrumented with 4 sensor nodes. Several readings were collected from the sensor nodes in both 2017 and 2018 and compared against a modeled response of the expected sensor response, determined through laboratory tests and recorded traffic on the bridge. In Figure 3(left), the deviation of the recordings from the model response is shown. A shift is observed on Sep. 3rd as crews prepared for the annual Labor Day walk (an event that is not modeled in our traffic data), and a large deviation was observed after the walk on Sep. 5th. Similarly, a model response (that neglected the Labor Day walk traffic) was compared against the measured sensor data in 2018, as shown in Figure 3(right), which also registered the event. Although this data cannot speak to the impact of the event, it does verify that this sensing method is able to capture that an anomolous event, as compared to a vehicle traffic model, can be captured.

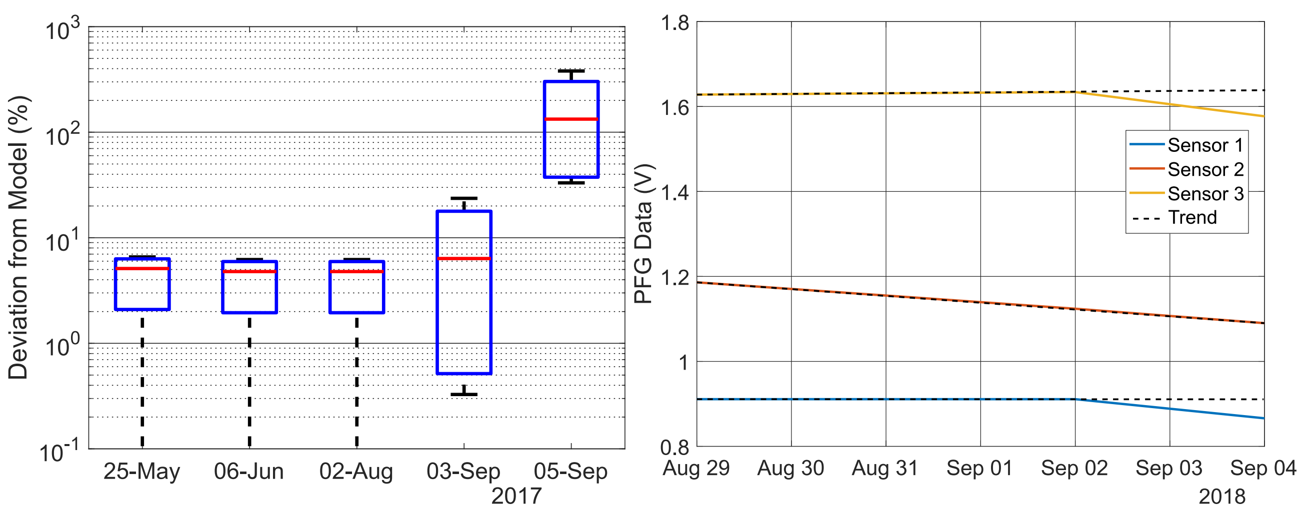

Figure 3: *Measurements from Mackinac Bridge 2017(left)(Aono et al., 2018), 2018(right)(Aono et al., 2019).*

5. Conclusions

In this paper we described a quasi-self-powered SHM sensor for continuous monitoring of rare events experienced by a civil infrastructure. The design integrates our previously reported self-powered PFG sensor module with a battery-powered wireless transmission module in an optimal configuration that can achieve continuous operation for durations greater 20 years. We have validated the operation of the system based on a deployment on the Mackinac Bridge in Michigan.

6. Acknowledgments

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