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Embedded H-gauge with Hybrid-Powered Sensors for Pavement Monitoring

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Abstract

One of the challenges in embedding sensors inside concrete and pavement highways is to be able to power and wirelessly interrogate these devices in real-time without taking the structure out-of-service. In this paper, we report a hybrid-powered H-gauge sensing platform that can be embedded inside pavements and can operate for years without any maintenance. This sensor platform is general enough to support a variety of transducers that operate in parallel and can wirelessly transmit relevant information to an external interrogator. Each sensor was equipped with a passive wake up circuitry that connects an embedded battery to the micro-controller only when it receives a valid signal from the interrogator. In this paper, we present prototypes of the hybrid sensor by integrating commercial off the shelf components along with temperature and humidity sensor and a custom built piezo-floating gate (PFG) sensor, that can continuously log cumulative strain statistics. In this paper, we also explore a completely self-powered variant of the platform that harvests the energy from the interrogator, as well as a quasi-self-powered platform that is designed to support long-range wireless interrogation. Deployment studies have bee conducted to determine the practical challenges and long-run performance of the proposed prototypes.

1. Introduction

Recent advances in autonomous vehicles and smart cities are facilitating the concept of intelligent infrastructure where large civil infrastructure like bridges, building, and pavements communicate with robotic vehicles in real-time. This information can then be used to plan better and safer practices for navigation and maintenance. This approach will obviate conventional monitoring practices involving visual inspections and manual cracking analysis, which are very costly, time-consuming and prone to inspection bias Xue (2012) and Weinmann (2004). In Aono (2016), we had proposed a framework of infrastructure internet-of-things (i-IoT) that uses an array of embedded sensors that can be wirelessly interrogated (illustrated in Fig. 1). We also reported a mechanism to package these devices in an H-gauge that facilitates deployment during the construction or compaction process, Aono (2018). In Kondapalli (2018), we proposed an embedded platform that can integrate a great variety of transducers. This platform not only enabled monitoring of the loading conditions experienced by the host structure like deflections, stress, and strain but also determine the environmental conditions like moisture and temperature. Also, the platform is customizable and allows provisioning of additional sub-modules based on the application. This universal interface enabled us to integrate our previously reported piezo-floating-gate (PFG) sensors that are used for continuous and long-term damage monitoring Chakrabartty (2013).

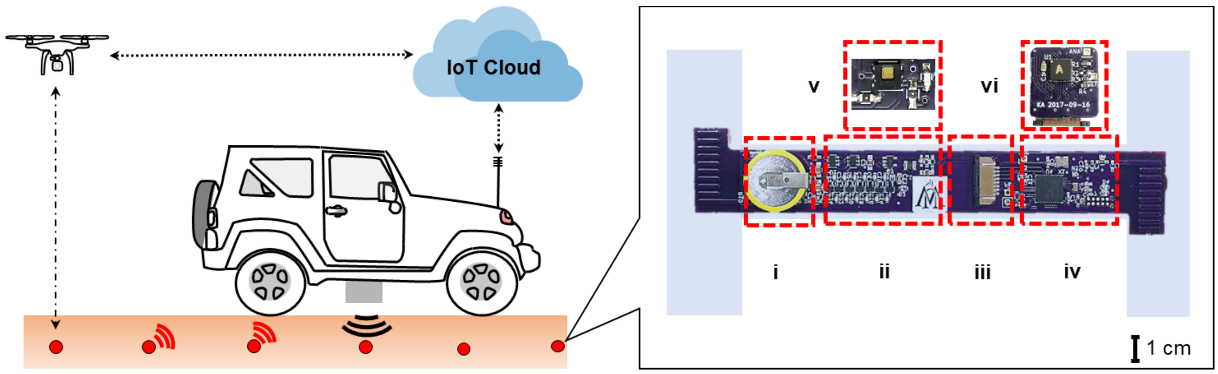

Figure 1: Left: Hybrid-Powered Sensor Framework for infrastructural Internet-of-Things (i-IoT) showing the possibility of long-term embedded sensing and interrogation using a vehicular platform or unmanned aerial vehicle. Management and processing of data can be performed remotely. Right: Hybrid-powered senor prototype showing the form factor of the sensor concerning the shape of standard H-gauge. Breakdown (i) Thin Mountable Battery (ii) The wake-up circuitry and power conditioning module (iii) Generic sensor interface (iv) Wireless Microcontroller (v) Mountable temperature and humidity Sensor (vi) Custom made self-powered structural health monitoring sensor.

However, the use of active sensing might not be suitable for long-term operation, and passive sensors might have performance limitations (sensitivity) to meet the needs of i-IoT. Previously we addressed this issue with a quasi-self-powered approach as reported in Aono (2018, Dec), Aono (2018), and Aono (2019). In this paper, we present a hybrid-powered embedded sensing platform to overcome the challenges. Fig. 1 shows an example of the sensor platform that is rated to operate for years and match the lifespan of the host structure. Also, the hybrid-powering approach minimizes the interrogation latency, reduces the downtime and can provide relevant data that can be effective for determining the structural condition. Fig. 1 also shows the relative size of the sensor that can be packaged in a standard H-gauge form-factor.

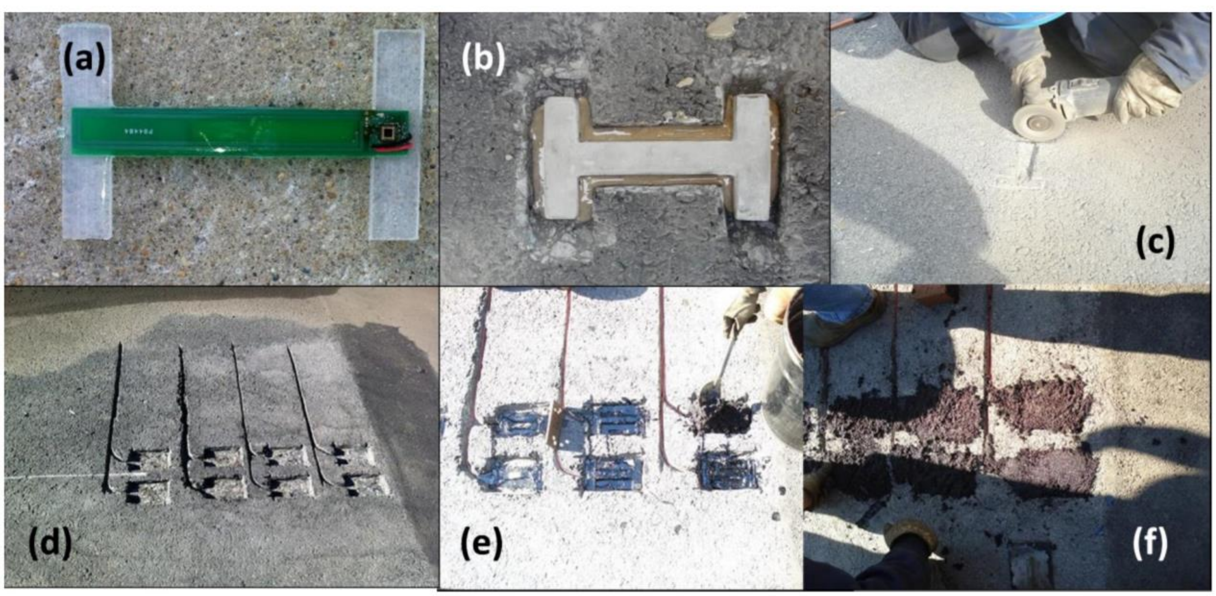

Figure 2: Deployment studies conducted earlier (a) self-powered sensor with RFID interface (b) packaged in the shape of H-gauge. (c) The process involved in deploying the sensor (d)-(f) and the test bed created for trialing our assembled prototypes.

Fig. 2 shows snippets from our earlier deployment studies which were reported in Chakrabartty (2013), Aono (2017), and Aono (2018). We plan to conduct similar studies using our proposed prototypes and compare the performance that can enable applications requiring long term reliable monitoring in an embedded fashion.

2. Hybrid Powered Sensor

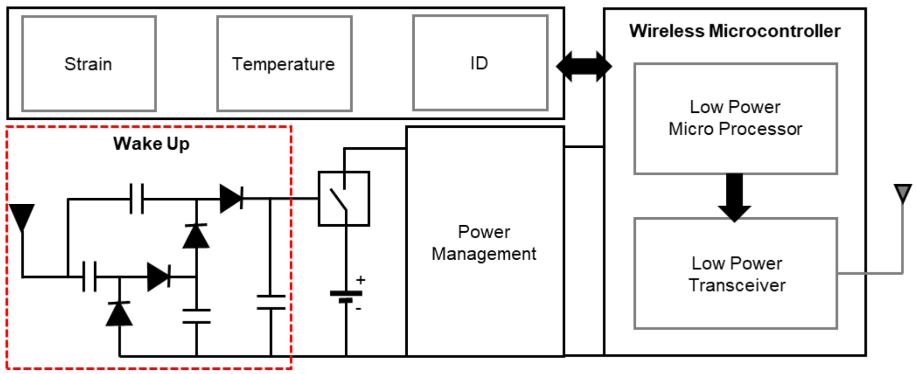

Figure 3: Architecture of Hybrid Powered Sensor showing the implementation of novel wake-up circuitry to enable long-term operation. It also shows the flexibility of several possible interfaces that can be attached directly to the wireless microcontroller showing the flexibility of the platform technology. Also, active transmission provided by the transceiver used shows the possibility of long-range communication.

The prototype is designed to serve static data (ID) and dynamic data (temperature, strain, etc.) through a wireless link, but only when an interrogation signal triggers a load-switch to connect a battery to the supply of a wireless MCU. The architecture of the prototype is depicted in Fig. 3. By using the energy harvesting stage as a wake-up circuit, the wireless MCU can be completely removed from the battery source, thereby reducing the current system consumption down to a few nA. Out of this current budget, only 10nA is spent on maintaining the charge on bypass capacitors and 35nA for the load switch's latching logic. When a wireless radio-frequency signal from an interrogator couple onto the antenna of the prototype, that built-up voltage is boosted and used for triggering the latch of the load switch. Once the wake-up circuitry is activated a wireless microcontroller (MCU) can operate as it would in a typical battery-based sensor node. After the MCU has collected the sensor readings and transmitted the data back to the interrogator, it will disable the load switch, thereby returning to an nA sleep mode.

Table 1: Table shows the extracted parameters from the assembled prototype highlighting the long-life span and faster interrogation time with relatively long-range communication.

Parameter	*Hybrid I2V Prototype*
PCB Area (cm^2)	22.15
Transmission Power (dBm)	8
Transmission Distance (m)	>10
Lifespan (yrs)	>20
Trigger Distance (m)	1
Trigger Latency (ms)	75
Average Power Dissipation (nW)	6 (rated 20 years)

Practical experiments were set up under laboratory conditions, and each of the assembled sensor was tuned to extract best case operation conditions when run in an RF chamber and also in open real-world setting Pochettino (2019). Wake up distance reported in Table. 1 is estimated using line-of-sight open air measurements which are close to real world scenarios. The startup latency of the hybrid prototype is greatly constrained by the wake-up circuitry Kondapalli (2018). A seven-stage Dickson charge pump is used in this particular implementation, which in turn triggers the timer, power management module to regulate the power going to the microcontroller. Care has been taken on the choice of the components based on this target application. Design level details were also discussed in our other works Pochettino (2018) and accepted as a novel concept by the RFID community in Kondapalli (2019).

The choice of sensors in hybrid sensor implementation was made particularly of the study of structural health and environment monitoring. The commercially available TI HDC2010 sensor is chosen for its low power, high precision operation. External sensors can also be easily interfaced with the PCB using an FFC connector. As shown in Figure 1 we used it to interface our custom built PFG sensor whose characteristics were discussed in detail in our earlier works Aono (2018, Dec).

2.1 Figure-of-Merit Comparison

To illustrate the benefits of the hybrid-powered topology, we use a figure-of-merit (FOM) that was introduced in (Kondapalli 2018) to compare different sensor platform technologies. The FOM compared the trade-offs involved when optimizing the platform for interrogation distance, interrogation latency, and operational life-span. The ideal FOM would involve collecting sensor data by an autonomous vehicle moving at expressway speeds (approximately 120 kph) which leads to a desired operational life, start-up latency, and transmission distance of 20 yrs, 100 ms, and 10 m, respectively.

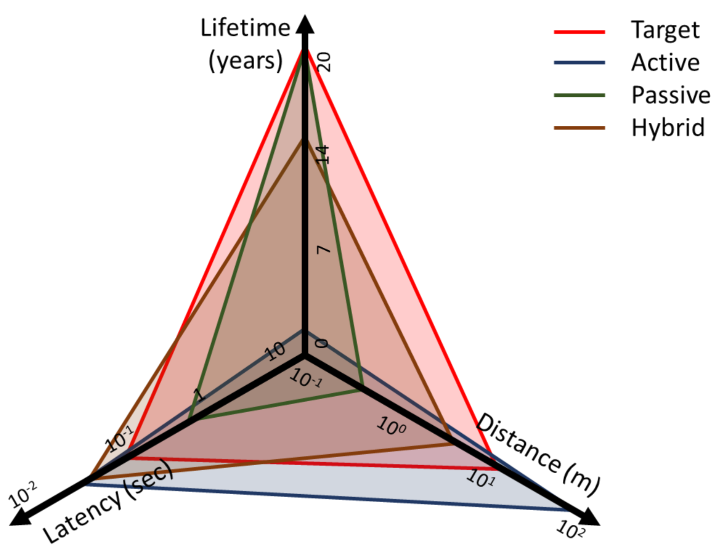

Figure 4: Comparison across the prototypes regarding distance, latency and the device lifetime and FOM estimated based on the overlap area of triangles.

Application-specific target parameters, like lifetime (l_A=20 years), startup latency (t_A=100 ms) and transmission distance (d_A=10 m), are graphically shown in Fig. 4 as a red triangle. Giving equal priority to each of these parameters, we define a figure of merit (FOM) as the overlapping area between the regions confined by the triangle edges of the prototype (l_P, t_P, d_P) and the target application given in equation (1).

$$\text{FOM} = \frac{Area\{\min(l_P,l_A),\max(t_P,t_A),\min(d_P,d_A)\}}{Area\{l_A,t_A,d_A\}} \quad (1)$$

More specifically, the estimated FOM values for active, passive and hybrid prototypes were summarized in Kondapalli (2018) as 0.2725, 0.5236 and 0.8227 respectively, hybrid being the highest. This scenario shows the advantage of the hybrid prototype over the other two modalities and is better suited for the target application with given constraints. These prototypes thus not only supports applications involving long-term embedded monitoring that needs interrogation at regular intervals (few days) but also capable for communicating with real-time traffic and enable new opportunities such as infrastructure-to-vehicle (I2V) communications.

3 Conclusion

In this paper, we proposed a hybrid-powered technique for designing sensing platforms that can be embedded inside pavement structures. We plan to deploy the platforms in H-gauges as shown in Fig. 2 and conduct SHM studies with the new prototypes. The hybrid-powered platform also paves a way to expand the platform technology to not only the applications involving SHM but also fits well into the framework that enables I2V applications which might be useful for next-generation autonomous vehicles.

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