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Heterogeneous tiny energy: An appealing opportunity to power wireless sensor motes in a corrosive environment

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HIGHLIGHTS

- Ultra-low ambient energy was scavenged to power the first of its kind wireless corrosion sensors.
- Three feasible tiny-energy sources were exploited for long-term corrosion monitoring.
- Automatic recharging control of heterogeneous tiny energy was proposed for human-free monitoring.
- Corrosion itself was applied as an energy source to power the wireless corrosion-monitoring motes.

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ABSTRACT

Reinforcing steel corrosion is a significant factor leading to the durability deterioration of reinforced concrete (RC) structures. The on-line monitoring of the corrosion of RC structures in a long-term, human-free manner is not only valuable in industry, but also a significant challenge in academia. This paper presents the first of its kind corrosion-monitoring approach that only exploits three heterogeneous tiny energy sources to power commercial-off-the-shelf wireless sensor motes such that the corrosion-related data are automatically and autonomously captured and sent to users via wireless channels. We first investigated the availability of these three tiny energy sources: corrosion energy, a cement battery, and a weak solar energy. In particular, the two former energy sources inherently exist in RC structures and can be generated continually in the service-life of RC structures, which beneficial for the prospects of long-term corrosion monitoring. We then proposed a proof-of-concept prototype, which consisted of a Telosb wireless sensor mote and an energy harvester in order to evaluate the feasibility and effectiveness of the ultralow-power ambient energy as a type of power supply in corrosion monitoring applications. The critical metrics for the holographic monitoring of RC structures, including electrochemical noise, humidity and temperature, were successfully acquired and analysed using a post-processing program. This paper describes a unique and novel approach towards the realisation of smart structural monitoring and control system in the practical engineering.

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1. Introduction

Reinforced concrete (RC) structures are the most important structural style in civil engineering. Unfortunately, the corrosion of reinforcing steel is the predominant factor causing the widespread premature deterioration of concrete infrastructures especially in areas exposed to de-icing salt or a coastal marine environment. In particular, the pitting corrosion is at such a high rate (up to 1 mm y^{-1}) that a rapid, remarkable reduction in the cross section of the reinforcing steel results [1,2], thereby leading to enormous subsequent costs for maintenance, restoration and replacement which are sometimes much greater than that of the initial construction cost. In some extreme situations, corrosion will finally lead to the collapse of RC structures. With the increasing impact of global warming and further deterioration of the environment, the surrounding conditions of RC structures are much harsher than ever before [3,4].

Due to the increased severity of corrosion, there is an urgency to diagnose the corrosion status of reinforcing steel on-line, such that

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an early warning system and the deployment of reliable maintenances resources and reinforcement plans can be provided in the field [5–7]. Over the past few years, most researchers have focused on advanced sensing technologies and health diagnostic approaches [8–10]. A large number of smart sensors, such as optic fibre sensors, piezo-electric ceramic sensors, cement-based strain sensors and nano-sized material-based sensors, have emerged and have been implemented in various structures in order to obtain useful physical and chemical parameters. According to the collected data, the serviceability of a structure can be estimated in terms of its safety and sustainability. Wireless sensor networking (WSN) technologies have attracted increased attention worldwide because their low-cost, flexible, and real-time properties in real-world deployments make it possible to dramatically reduce labour costs and to enhance the application fidelity in corrosion monitoring [11–14]. In fact, WSNs have been adopted to monitor the status of structures in many fields, e.g., infrastructures, vehicles, industrial machines, buildings and home-based devices [15–21].

While WSN technology seems to be a very promising means to realise in situ, real-time, and on-line corrosion monitoring and control [22–25], the durability of their power sources for long-term (e.g., ten years or longer) use is questionable due to the intrinsic battery constraints of wireless sensor motes. The sensor motes of WSNs are typically powered by traditional batteries (or even rechargeable batteries), which are often very limited in capacity and are leakage-prone. To achieve a longer operation, wireless sensor mote batteries are frequently replaced or recharged; however, these practices are rather difficult or even impossible to execute in practical civil engineering [26–30]. As a result, a constrained energy supply is the overriding challenge facing WSN applications for long-term, human-free corrosion monitoring.

Motivated by the need for a long-term and efficient RC structural monitoring and control, this paper presents the first of its kind corrosion-monitoring sensor system powered by heterogeneous tiny-energy sources and addresses two critical aspects of building this system: (1) exploiting and scavenging three major in situ heterogeneous ultralow-power energy sources continually generated from the natural evolution of the RC structures or from the surrounding environment, and (2) designing and implementing an energy control policy for wireless sensor motes such that the system can independently operate in a long-term, human-free manner, while meeting corrosion-monitoring application requirement for data fidelity.

This study is inspired by one interesting and exciting fact: the electrochemical corrosion process is an energy-releasing process; i.e., there exists tiny-energy delivery phenomenon (hereafter referred to as corrosion energy) in a series of electrochemical reactions. Compared with other traditional energy sources, the corrosion energy is the intrinsic energy of RC structures nearly throughout their entire service-life cycle. Essentially, the corrosion process is an electrochemical process. When sufficient chloride ions (from de-icing salts or from seawater) penetrate into the reinforcement or as the pH value of the pore solution becomes more acidic due to the carbonation reaction $Ca(OH)_2 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2 + CaCO_3$, the protective film is destroyed and the reinforcing steel is depassivated. The fundamental electrochemical reactions occurring at the anode and cathode regions are $Fe \rightarrow Fe^{2+} + 2e^-$ and $1/2O_2 + H_2O + 2e^- \rightarrow 2OH^-$, respectively [1]. Although the entire corrosion process is extremely complex, there is an overall electron transfer inside the barrier layer or on the surface of the reinforcing steel. The energy stored in the Fe crystals during the melting process of iron ore is gradually released as a tiny corrosion current and the materials change from a crystalline state to an amorphous state during the corrosion process. Such an intrinsic source of tiny-energy has a huge potential advantage in the application of a self-powered WSN for a structural health monitoring and control (SMC) system in civil engineering. On the other hand, corrosion sensitive materials, such as Mg, Zn, Al and their alloys, also produce electric energy during the cathodic protection (CP) process of RC structures and have been widely applied in sacrificial anode cathodic protection (SACP) systems The SACP technique is based on the principles of thermodynamics and kinetics. The reinforcing steel in RC structures is polarised against the equilibrium corrosion potential to a negative value by the corrosion sensitive materials. As a result, a net cathodic current will flow across the sacrificial anode/electrolyte interface to the protected target. The reinforcing steel is then under cathodic protection when it is sufficiently negatively polarised to the equilibrium corrosion potential which reduces the dissolution rate of the reinforcing steel [31]. Regardless of the CP mechanism, electrical energy is released and delivered. Therefore, corrosion-sensitive materials used in SACP systems should be able to provide another potential, significant and valuable source to power WSNs for the corrosion monitoring and control system of RC structures.

Through preliminary investigations, we find such an appealing opportunity to power wireless corrosion-sensing motes by utilising only the tiny-energy naturally stored in RC structures, which has never been studied and valued in the literature. In fact, from the perspective of environmental energy sources, there are a number of fully realised renewable energies that could be employed to drive wireless sensor motes, including solar, piezoelectric, electrodynamic, thermoelectric, and electromagnetic energies [32–34]. However, the adoption of any one of these energy sources would require their devices to be placed inside or outside the RC structure to capture their corresponding events (signals). The variability and complexity of this approach complicates the construction of RC structures and could also significantly impair the integration of RC structures. For instance, if solar energy was used to power the wireless corrosion-sensing motes, we would encounter implementation issues in terms of the design and deploying cost: (1) long wires are needed to connect the solar panels and the sensor motes embedded in RC structures in advance, (2) a more complicated energy storage platform is required to store sunlight energy, and (3) direct sunlight is not always available. Using the energy continually produced by the RC structures themselves to monitor their corrosion status is not only a promising concept, but has a potentially large impact on corrosion monitoring.

Our investigation represents a bold attempt and a tremendous step towards the realisation of SMC in practical civil engineering. Additionally, our work will proposes a series of new and valuable topics in designing long-run wireless sensor networks, such as designing an efficient routing policy over an intermittent network topology as a result of varying the energy harvesting requirement. We first studied corrosion energy, designed the cement battery and analysed their performances as power sources. Then, we built a small-scale proof-of-concept prototype with an automatic energy control scheme, which harvested tiny-energy from heterogeneous energy sources to power commercial off-the-shelf wireless sensor motes. It is worthy to note that the presented investigation primarily focuses on the feasibility of using the heterogeneous tiny-energy stored in and around RC structures to power the wireless corrosion-monitoring sensor motes. In the future studies, we aim to design systematic wireless corrosion-sensing platforms driven by the proposed tiny energies. The paper is organised as follows. Section 2 briefly introduces the experiment. Section 3 describes the performance of the corrosion energy, the corrosion-sensitive cement batteries, and the weak solar energy and presents the results and discussion of the wireless mote driven by heterogeneous sources. Section 4 summarises this study.

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