Constructing Smart Buildings with In-concrete Backscatter Networks

Zheng Gong, Zhenlin An, Jingyu Tong, Donghui Dai, Lei Yang
Department of Computing, The Hong Kong Polytechnic University
{gz,an,tong,dai,young}@tagsys.org

ABSTRACT

Given the increasing number of building collapse tragedies nowadays (e.g., Florida condo collapse), people gradually recognize that long-term and persistent structural health monitoring (SHM) becomes indispensable for civilian buildings. However, current SHM techniques suffer from high cost and deployment difficulty caused by the wired connection. In this work, we collaborate with experts from civil engineering to create a type of promising self-sensing concrete by introducing a novel functional filler, called EcoCapsule–a battery-free and miniature piezoelectric backscatter node. We overcome the fundamental challenges in in-concrete energy harvesting and wireless communication to achieve SHM via EcoCapsules. We prototype EcoCapsules and mix them with other raw materials (such as cement, sand, water, etc) to cast the self-sensing concrete, into which EcoCapsules are implanted permanently. We tested EcoCapsules regarding real-world buildings comprehensively.

CCS CONCEPTS

• **Hardware → Wireless integrated network sensors**.

KEYWORDS

Structural Health Monitoring, Backscatter Communication, Ultrasonics

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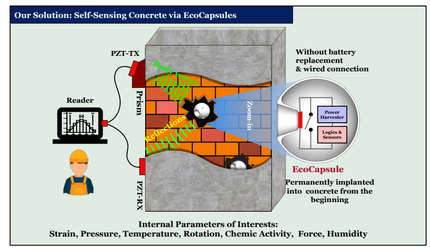
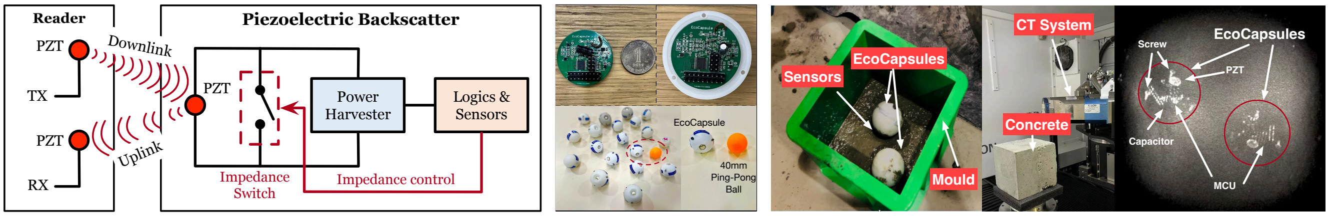


Fig. 1: SHM Solution via EcoCapsule The operator can intrusively attach the transmitting and receiving PZTs onto the wall to communicate with the EcoCapsules implanted early, thereby acquiring the SHM-related data from the sensors.

1 INTRODUCTION

On June 24, 2021, Champlain Towers South, a 12-story beachfront condominium in the Miami suburb of Surfside, Florida, United States, partially collapsed, eventually resulting in a tragedy of 98 deaths [3] that shocked the whole world. According to the investigation, the main contributing factor to the collapse is the long-term reinforced concrete structural support degradation in the ground-level parking garage under the housing units. This degradation is due to water penetration and corrosion of the reinforcing steel [6]. Nowadays, safe and dependable architectures play fundamental and crucial roles in modern society. However, concrete architectures inevitably suffer from aging and environmental degradation. The best approach to preventing buildings from abrupt collapse is to conduct structural health monitoring (SHM). Through sensing techniques proposed in the field of civil engineering, they are all *intrusive* because they require *cables* to connect the embedded sensors in the concrete. The RF-based wireless sensor network (WSN) [8] was introduced as a promising alternative solution to dissolving cable bonds. However, the WSN is still rarely employed for SHM in practice because of their frequent battery replacements.

In this demo, we push this vision forward by introducing a battery-free, computable, sensible, and connectable filler called EcoCapsule. This pint-sized and cost-effective piezoelectric backscatter sensor can be wirelessly charged and connected via elastic mechanical waves. They can be implanted permanently into a building without follow-up maintenance, thereby ensuring the structure intact of the target building during the running period. As shown in Fig. 1, when acquiring structural parameters of interest (e.g., strain, acceleration, etc), the operators attach the transmitting and



(a) Illustration of PBS (b) EcoCapsules (c) Casting and CT scan of EcoCapsules

Fig. 2: Principle, Prototype, and Fabrication of EcoCapsules (a) shows the piezo-acoustic backscatter system; (b) shows the prototype of EcoCapsule; (c) shows the casting scene, CT scan scene, and imaging result.

receiving piezoelectric transducers (PZTs) on the surface, which exert well-designed elastic waves into the concrete to power up EcoCapsules for sensing and communication. Afterward, EcoCapsules send back data by using the backscatter communication, i.e., reflecting or not reflecting elastic wave to modulate bit one or zero.

We prototype dozens of EcoCapsules (Fig. 2(b)). Each consists of a mechanically fabricated PZT, a custom-made motherboard that incorporates the energy harvesting unit, a microcontroller, and an extensible peripheral interface that integrates with various sensors (e.g., strain, temperature, and humanity sensors). Our results demonstrate that EcoCapsule implanted into real-life concrete can be successfully powered up and wirelessly connected through the continuous body waves. We can achieve a maximum power-up range of more than 6 m and a throughput of up to 13 kbps. We also demonstrate that EcoCapsules can be implanted into various types of concrete, including the ultra-high-performance fiber-reinforced concrete (UHPFRC), whose compressive strength is up to 215 MPa, thanks to the stressless shell design. More details can be found in our full paper in SIGCOMM 2022 [10].

2 DESIGN OF ECOCAPSULE

Although piezoelectric backscatter systems (PBSs, see Fig. 2(a)) have been successfully applied to underwater communication [5], it is challenging to apply the PBS in a concrete environment (solid media). First, the propagation of mechanical waves (i.e., elastic waves) in solid materials (e.g., concrete) is much more complicated than that in liquid materials (e.g., air or water). In particular, five or above multiple modes are activated, resulting in severe intra-symbol interference at the receiver side (i.e., EcoCapsule), degrading the efficiency of energy harvesting and symbol decoding. We design a *wave prism* to deal with the issue mentioned by eliminating redundant modes but maintaining the S-wave as the single carrier. We leverage Snell's law and design prisms in different angles to filter out the S-mode of body waves. Second, the external pressure that an EcoCapsule receives from the surrounding concrete is much higher than that a sensor receives in water. We design spherical and stressless shells to overcome such a harsh deployment environment for protecting the internal circuity from being cracked or deformed. Besides,

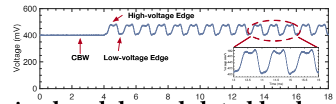


Fig. 3: Received and demodulated backscatter signal.

the PZT has the ring effect [9], which brings in the inter-symbol interference and decuce the throughput. To solve this issue, we take advantage of the resonance effect and dual-frequency-based FSK to achieve the OOK at the receiver side. In particular, the PZT is vibrated at a resonant or non-resonant frequency of the concrete. The concrete naturally suppresses the waves at non-resonant frequency because of the off-resonance. EcoCapsule nodes eventually receive the high/low amplitude bits similar to the OOK encoded bits.

3 DEMO OF ECOCAPSULES

Fig. 2(b) shows our fabricated EcoCapsule prototypes, which are in the shape of spheres with small sunken mouths. Each one is the size of a standard ping-pong (i.e., 4.5 cm diameter). Such design is dedicated to equalize the external stress. The core of EcoCapsule is a battery-free processing board, which is designed and fabricated on a round two-layer printed circuit board (PCB) (3.5 cm diameter). It is a general-purpose and extensible computing platform for long-term SHM. The hardware design is inspired by WISP [7] and PAB [5]. Each EcoCapsule cost approximately 10 USD. The circuit components are hand-soldered on the PCBs and individually tested. The detailed hardware and software design has been released on Github [2] and our project website [1].

In this demo, we will show how EcoCapsule helps construct smart buildings. We use a standard mould to cast self-sensing concrete blocks, as shown in Fig. 2(c). These blocks are the basic units to build a house. In practice, we can also directly pour nodes into the load-bearing walls or columns in practice. We use a CT scan machine [4] to examine the structure intactness after the concrete blocks are solidified. Fig. 3 plots the received and demodulated baseband signal where EcoCapsule starts to backscatter from 4 ms.

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