Opportunities of Motion-Powered IoT Systems

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Abstract

Kinetic energy harvesting (KEH) technology is one of the most promising energy solutions for everlasting and ubiquitous sensing applications. However, handling ambient fluctuating sources and interdisciplinary co-design still prevent its rapid development. In this study, based on cyber-electromechanically synergistic co-design, we build a reconfigurable, flexible hardware platform, explore a series of robust KEH-powered battery-free applications, and propose a comprehensive energy analysis for the complete system.

Biography

Xin Li is a Ph.D. (2018-2022) candidate at ShanghaiTech University. He is also with the Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, and University of Chinese Academy of Sciences. His research interests include kinetic energy harvesting, intermittent computing, ubiquitous computing, and battery-free IoT. He was a recipient of the First Place of the International Conference on Embedded Wireless Systems and Networks (EWSN) Dependability Competition in 2019, the First Runner Up of the IEEE Industrial Electronics Society (IES) Inter-Chapter Paper Competition in 2019, and the Best Student Hardware Competition Finalist of the ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS) in 2020. His research advisor is Professor **Junrui Liang**, and he is grateful for the collaboration with **Hong Tang**.

1 Introduction

Energy harvesting enables a maintenance-free installation for ubiquitous sensing systems. It uses different ambient sources such as solar, radio frequency (RF), and vibration to power the low-power wireless sensor. These battery-free Internet of Things (IoT) systems have been rapidly penetrated different applications, such as body implants and everlasting sensors in extreme regions [1]. However, the power fluctuation of ambient sources challenges the design of these systems against unstable energy supplies and inevitable energy outages. Their computing part should be fundamentally different from conventional systems because battery-free devices violate one of the most basic computing assumptions, that is, a stable power supply. The developers must rethink the relationship among energy source dynamics, power management circuit, and computing in a battery-free IoT system.

In the last ten years, many studies have been proposed to solve the computing challenge under unstable energy supply from different aspects. Unfortunately, even with these cutting-edge technologies, such as sophisticated harvester design, energy-neutral power management, and intermittent/transient computing, existing battery-free IoT systems are still less reliable than their battery-powered counterparts. In particular, for kinetic energy harvesting (KEH) systems, although a lot of innovative mechanical harvesters and electrical circuits have been proposed to broaden the energy harvesting bandwidth and improve the electromechanical conversion efficiency. Few studies can cross the boundary of different disciplines and develop a complete KEH-powered system solution. Moreover, most KEH based cyber designs only use the simplest linear energy harvesting structure or even neglect actual mechanical dynamism. They often focus on demonstrating individual harvester, software, or circuit design.

The mechanical kinetic energy from the ambient vibration/motion often needs to be appropriately processed first in the mechanical domain, then converted into electrical energy with an electromechanical transducer. Mechanical transformer serves as a bridge between energy sources and electromechanical energy transducers in energy harvesting [4]. By inserting a mechanical energy buffer between the kinetic energy source and the electromechanical transducer, KEH offers an opportunity to guarantee stable operations under unstable ambient source fluctuations. Such a feature is unprecedented than its solar and RF counterparts.

In our recent research, we investigated the opportunities and role of KEH in battery-free IoT systems. We gave a comprehensive energy analysis among mechanical, electrical, and cyber parts. We have also built several KEH-powered systems based on cyber-electromechanically synergistic co-design. It provides valuable insight into the design of battery-free IoT solutions.

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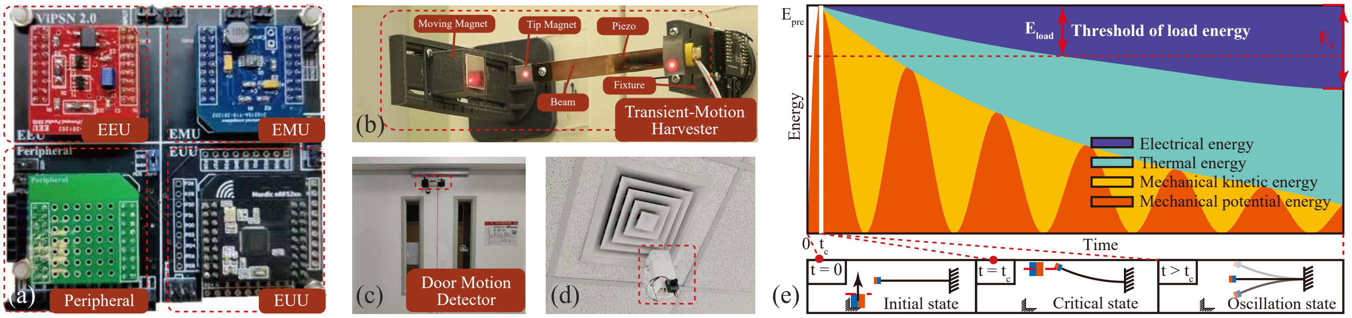

Figure 1. Research overview. (a) ViPSN platform. (b) Catch-drag-release harvester in ViPSN-E. (c) ViPSN-E as a door motion detector. (d) ViPSN-Cam. (e) Energy flow in ViPSN-E after a plucking motion.

2 Research Overview

KEH-powered IoTs need to be customized for handling various kinetic sources and task functions in real-world applications. They often require specific hardware and software. Designing a complete KEH-powered IoT system from scratch is costly and time-consuming. It covers at least three disciplines: mechanical engineering, electrical engineering, and computer engineering. It is one of the main obstacles stopping KEH systems from mainstream IoT applications. ViPSN (acronym of vibration-powered sensing node) [3] is the first open-source[1] development platform specified for KEH. It provides all necessary modules for rapid prototyping and customizing KEH systems, including a vibration emulator as the energy generation unit (EGU); an electromechanical transducer as the energy transduction unit (ETU); a power-boosting interface circuit as the energy enhancement unit (EEU); a dc-dc regulator with energy-level indicating signals as the energy management unit (EMU); a Bluetooth low energy (BLE) module as the energy user unit (EUU); and a mobile app as the edge demonstration unit (EDU). Fig. 1 (a) shows the ViPSN 2.0, which adds a rapid prototyping peripheral module. By keeping good monitoring of the stored energy and inserting an energy build-up phase among the cold-start and computing operation phases, ViPSN can efficiently and robustly operate under various forms of kinetic excitations, such as harmonic, intermittent, or transient cases. In addition, it also supports a variety of kinetic energy transducers, including piezoelectric, magnetoelectric, and triboelectric transducers.

To better analyze energy harvesting, flow, and distribution of the KEH system, we explore two extreme conditions. One is transient kinetic energy harvesting, such as swinging an arm, opening/closing a door, and holding/releasing objects. The other is heavy load energy consumption, such as streaming media data transmission and image processing. As shown in Fig. 1 (b) and (c), based on the ViPSN platform, we developed ViPSN-E [2], which makes full use of every discrete transient motion for realizing a self-powered and self-sustained motion detection. Given this limited energy supply, we reconsidered the role between the harvester and the sensor. Via incorporating the nonlinear dynamics of the mechanical structure and software program of the cyber system, ViPSN-E can simultaneously act as a transient harvester and a wireless motion director. Fig. 1 (d) shows ViPSN-Cam, a battery-free camera via wind energy harvesting. Through an energy management circuit and application task scheduling co-design, ViPSN-Cam can maintain the optimal power input and robustly perform image acquisition, processing, and wireless transmission.

Fig. 1 (e) shows the energy flow process in a catch-drag-release harvester after a single plucking excitation. In each plucking motion, the cantilever beam is bent by a driving magnet. It is released after the magnet pass through a critical position. After the release, the beam starts to oscillate until the vibration is damped out. In other words, this plucking-based approach pre-charges an energy harvester with a specific amount of initial potential energy, which is released immediately, inducing a damped oscillation. This process is termed *potential energy pre-charging*. The amount of pre-charged potential energy of a harvester can be guaranteed by properly designing the mechanical structure. Compared to its solar and RF counterparts, this KEH design offers a unique feature of the on-demand operation. Real-world experiments have validated the robustness of ViPSN-E in battery-free motion detection. More exploration of KEH technologies will open a bright future for more battery-free IoT applications.

3 References

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