Kinetic Energy Harvesting Toward Battery-Free IoT: Fundamentals, Co-Design Necessity and Prospects

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Abstract: Energy harvesting (EH) technology is developed with the purpose of harnessing ambient energy in different physical forms. Although the available ambient energy is usually tiny, not comparable to the centralized power generation, it brings out the convenience of on-site power generation by drawing energy from local sources, which meets the emerging power demand of long-lasting, extensively-deployed, and maintenance-free Internet of Things (IoT). Kinetic energy harvesting (KEH) is one of the most promising EH solutions toward the realization of battery-free IoT. The KEH-based battery-free IoT can be extensively deployed in the smart home, smart building, and smart city scenarios, enabling perceptivity, intelligence, and connectivity in many infrastructures. This paper gives a brief introduction to the configurations and basic principles of practical KEH-IoT systems, including their mechanical, electrical, and computing parts. Although there are already a few commercial products in some specific application markets, the understanding and practice in the co-design and optimization of a single KEH-IoT device are far from mature, let alone the conceived multiagent energy-autonomous intelligent systems. Future research and development of the KEH-IoT system beckons for more exchange and collaboration among mechanical, electrical, and computer engineers toward general design guidelines to cope with these interdisciplinary engineering problems.

Keywords: kinetic energy harvesting; battery-free solution; Internet of Things; co-design

DOI: 10.12142/ZTECOM.202101007

https://kns.cnki.net/kcms/detail/34.1294.TN.20210309.0902.002.html, published online March 9, 2021

Manuscript received: 2021-01-22

Citation (IEEE Format): J. R. Liang, X. Li, and H. L. Yang, "Kinetic energy harvesting toward battery-free IoT: fundamentals, co-design necessity and prospects," *ZTE Communications*, vol. 19, no. 1, pp. 48–60, Mar. 2021. doi: 10.12142/ZTECOM.202101007.

1 Background

The on-going development trend of the Internet on Things (IoT) technology has attracted a lot of interests from the communication and computer research communities, as well as numerous investments in the related industries. The topics of wireless communication and computational intelligence have caught the most attention. For wireless communication, existing technologies can be categorized according to their spatial scopes. Rooted from the radio-frequency identification (RFID) technology, the near field communication (NFC) is already very mature for connecting things in a very short distance, that is to say, less than several centimeters. For a longer distance around a human user, ranging from a few centimeters to a few meters, the wireless personal area network (WPAN) is also very mature. Bluetooth and Zigbee are two of the most prevailing WPAN technologies for the IoT. Unlike general Wi-Fi communication, the low-power feature is usually emphasized in the WPAN for the IoT. To connect things in an even longer distance, we need the low power wide area network (LPWAN). Narrow-band Internet of Things (NB-IoT) and Long Range (LoRa) technologies are the two most representative technologies of LPWAN. In particular, NB-IoT is compatible with the existing cellular networks and operates in licensed frequency bands; it might be constructed as essential infrastructure for communication in the visible future.

Wireless communication is the main battlefield of IoT technology. As mentioned above, different wireless communication technologies for different targeted ranges have already been proposed and received extensive investigations. On the other hand, we should also keep in mind that all things with sensing, computing, or communication capabilities need electric power to run. Compared with wireless communication, the wireless power transfer or power generation technologies in different distance ranges are far from mature. The near-field case is the most mature, given the rapid development of wireless power transfer (WPT) technology in the last two decades[1]. For the WPAN range, electric power can hardly be transferred efficiently to passive devices, which do not carry long-term energy storage, on edge. The WPAN-level backscatter communication has recently attracted a lot of research interest[2–3]. These backscatter devices only scavenge tiny energy from the transmitter to alter their radio frequency (RF) characteristics and deliver low throughput data, rather than actively send back signals[4]. For the things in the wider WPAN or LPWAN scopes, wireless power transfer is invalid, as the power attenuation of the RF signal is proportional to the cube of the distance between the transmitter and receiver. To keep things connected in such a wide range, they must bring their own energy storage or be able to harvest energy by themselves in their surroundings[5–6]. In the long run, the energy harvesting (EH) technology is the only option to provide continuous power supply to many scattered things for supporting their everlasting operation[7–8]. Once all things become energy-autonomous, many benefits, such as maintenance-free operation and ubiquitous deployment, can be achieved. The EH technology is naturally linked with the battery-free IoT applications; otherwise, the tiny ambient energy means almost nothing compared with the centralized large-scale power generation or even the storable energy in chemical batteries[1]. Therefore, at the current stage and from the practical point of view, EH should be first regarded as a backbone technology toward the realization of massively deployed and everlasting low-power IoT, rather than taken as a substitution of general power generation technology. The ambient energy sources are usually characterized as volatile sources, like most renewable sources such as solar and wind power. The EH devices should be designed not only to handle these volatile sources but also to closely meet the demand of low-power IoT in time. The scarce and volatile energy supply in practice and the reliable and timely information demand in expectation together impose the biggest challenge in the co-design and optimization of EH-IoT systems.

2 Kinetic Energy Harvesting

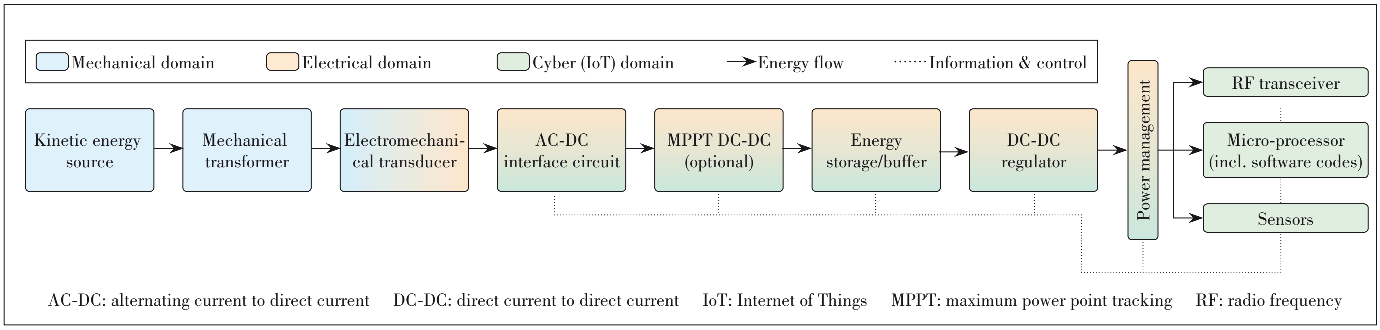
Besides harvesting energy from the conventional renewable ambient energy sources such as the solar source[2], the other most popular and extensively investigated EH technologies include the RF EH, thermoelectric EH (TEH), and kinetic EH (KEH). Among those energy sources, the kinetic one is unique. On the one hand, electric machine technology has maturely been used for many years for large-scale electromechanical power generation. Kinetic energy is a must step in most centralized power generation processes. For example, in coal-fired, nuclear, and hydro-power plants, energy is converted through turbines and electromagnetic generators into electricity. On the other hand, the small-scale kinetic energy harvesting technology has caught people's attention for just one or two decades. Different from the centralized generation and power grid facilities, in which the power flows among the power generation, transmission, distribution, and utilization stages are intensively and precisely controlled, a small-scale KEH-IoT is a self-contained and energy-autonomous system. It has to be sustainable against environmental uncertainties (intermittent or random vibrations), and execute the sensing, computing, and communication functions correctly and timely according to the information demand.

In a word, toward practical application, it is inappropriate to merely emphasize the KEH design as either a mechanical dynamics problem, or an electrical power conversion problem, or a computational problem. Perfect coordination among mechanical dynamics, electrical power conversion and information processing is what we are looking for toward the successful development and application of a KEH-IoT system.

2.1 System Overview

A KEH-IoT system connects three major physical domains: the mechanical, electrical, and cyber domains. **Fig. 1** shows the general block diagram of a KEH-IoT system, in which the three domains are distinguished with different colors. The mechanical kinetic energy excites the vibration or movement of the mechanical structure. A mechanical transformer transfers the excitation to the transducer input with a specific force or displacement ratio to match the kinetic source and transducer mechanical characteristics. An electromechanical transducer converts the mechanical energy into an electrical one, which is in an AC (alternating current) form. Following the transduc-

1. The available power from the ambient energy sources is very tiny, usually from micro-watt to watt scales.
2. Different from the large-scale solar panel, the solar energy harvesting is usually referred to as the on-site power generation using small photovoltaic panels.

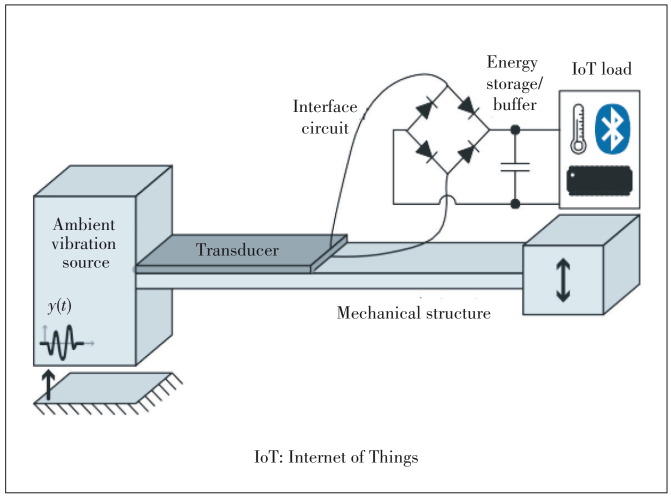


▲**Figure 1. Block diagram of a kinetic energy harvesting (KEH)-IoT system**

er electrical output, there are several stages of power electronic modules for adapting the extracted power into a stable logic voltage level. The interface circuit carries out the AC-DC (alternating current to direct current) conversion, which is usually called rectification. At the same time, it can collaborate with a following and optional DC-DC maximum power point tracking (MPPT) stage for extracting more power from the vibrating mechanical structure. The extracted energy is stored in a storage device, such as a chemical battery, a super-capacitor, or sometimes just a small buffer capacitor for immediate utilization. Since the storage level might be floating, which is likely to give a fluctuating output voltage, a DC-DC regulator is necessary for providing a stable and reliable voltage level for powering digital electronics.

In the previous studies, people mostly studied a KEH system by considering the theoretical model and practical design of its mechanical structure and/or electrical circuit[9–11]. However, recent research on energy harvesting based IoT systems has shown that, when doing computation with scarce and volatile energy supply, there might be more stories than most people, who are working on mechanical or/and electrical designs, have thought[12]. Therefore, the effect of an IoT load should not be simply taken as an equivalent constant resistive load. In a KEH-IoT system, the dynamics produced by its computing demand is as important as the electromechanically coupled dynamics. In Fig. 1, the cyber part is usually composed of a microprocessor, sensors, the RF transceiver, the digital interface and control of the power converters, and more importantly and necessarily, the software codes. The power management hardware design and the embedded software act crucial roles in moderating the KEH harvested power (as an income) and IoT information demand (as an outcome). The energy and information flows within a KEH-IoT system are also illustrated in Fig. 1.

To give a more intuitive idea of a KEH-IoT system, **Fig. 2** shows a typical piezoelectric KEH system. The base vibration corresponds to the kinetic energy source. The cantilever beam and proof mass together act as a mechanical transformer. The electrical part includes a bridge rectifier for AC-DC rectification and a filter capacitor as the energy storage/buffer. The IoT load is not specified here. It might carry out some sensing, computing, or communication functions in general. Given the



▲**Figure 2. A typical piezoelectric KEH system**

scarce energy that can be harvested with a piezoelectric energy harvester, the hardware and software of the IoT load must be carefully designed by referring to the energy-aware computing technology.

2.2 Mechanical Design

The modeling and design of KEH systems have attracted a lot of research interest from mechanical engineers during the last two decades[10, 13–15]. It is intuitively understandable that removing energy from a vibration system must result in an increase of its damping coefficient. The damping effect was quantitatively investigated in the previous studies[16–18]. In some designs, harvesting energy might also change the system dynamics from the electrical side as well[19–21]. A large branch of studies focuses on the theoretical modeling of mechanical dynamics when the system is subjected to different loading conditions, i.e., to understand the behavior of the KEH system in terms of vibration dynamics and harvested power[22–23]. Another biggest category of studies investigated how to modify or redesign the structural configurations toward some objectives, such as

• enhancing the harvesting capability by matching the stroke or force between the mechanical energy source and the transducer mechanical-side input [24];

• broadening the harvesting bandwidth[25];
• adapting to vibrations from different spatial directions[26];
• adapting to different types of vibration patterns, such as harmonic, intermittent, or random vibrations[27];
• better exploring different kinetic sources, such as human motion[24], fluid[28], or gust[29];
• focusing elastic wave energy for better feeding the energy harvester[30–31].

As illustrated in Fig. 1, two of the most important mechanical aspects of a KEH system is the kinetic energy source and mechanical transformer. Different from their solar and RF counterparts, and even the thermoelectric energy sources, kinetic sources might have a lot of different possible patterns and affluent dynamic characteristics. Environmental vibrations are usually characterized as random excitation[32–33], which has a very broad power spectrum. Some machine vibrations are harmonic[22–23] or periodic[27, 34], i.e., only component vibrations at some narrow frequency bands. Besides, some movements, in particular the fluid movements, are with constant current[28, 35]; while some others are shock- or impact-based[36–37]. Therefore, there seems no such a universal structure that can optimally harness energy from all kinds of vibration conditions. Customization is a must for any given vibration/motion scenario. Understanding the characteristics of different mechanical vibration sources is very important for designing their specific KEH systems.

Considering the mechanical mismatch between the source and transducer, in terms of strain or stress range, resonance frequency, etc., a mechanical transformer (a kind of rigid-body or deformable mechanism) must be used to accommodate the vibration source and transducer input. Many scholars have made in-depth discussions on strain range matching[38–39] and frequency matching[14–15]. In particular, numerous mechanical designs were proposed to broaden the energy harvesting bandwidth. These designs include the resonant tuning[40], multi-mode energy harvester[41], frequency-up design[27] and nonlinear structure[42].

The electromechanical transducer, which enables the power transformation from mechanical to electrical form, is one of the essential components in a KEH system. A transducer has both mechanical and electrical characteristics, which are mutually influenced or coupled in short. The most investigated electromechanical transducers used for KEH include the electromagnetic[43], piezoelectric[10, 13, 43–44], and electrostatic[45–46] ones. **Table 1** summarizes the pictures and features of these three types of transducers. Due to their different coupling features, people tend to use them in some specific or preferred scenarios. For instance, when the kinetic energy is associated with rapid movements, it is more appropriate to use electromagnetic harvesters; when it is associated with large force or structural deformation, it is more suitable to use piezoelectric harvesters. A mechanical transformer, such as a lever or gearbox, can help match the vibration source and transducer in terms of their force or displacement ranges. Electrostatic harvesters are more suitable in micro-electromechanical system (MEMS) scale designs. Some flexible transducers, such as triboelectric and soft piezoelectric materials, are very popular in the research communities nowadays[47–49]. Their electrical principle can be referred to as either of these three types of transducers. The studies of high power-density and flexible transducers have also attracted a lot of research interests from material scientists[50–53].

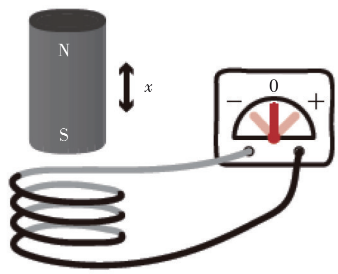
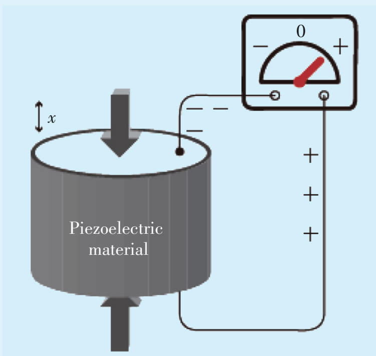
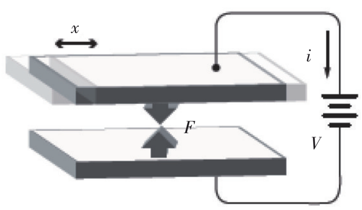
2.3 Power Conditioning Circuit

The electric circuit design was another research hot spot during the last two decades. As shown in Fig. 1, the electrical parts in green connect the mechanical parts in khaki and the cyber parts in blue. The modern power electronics technology provides an effective solution to better harness the incoming fluctuating power flow and adequately satisfying the energy demand for timely information processing. The power conditioning circuits built from fundamental power electronics play an essential role in the KEH-IoT system[54]. They should be designed toward some objectives, such as

• extracting more power by making proper intervention to the source dynamics;
• achieving high power conversion efficiency under load variation for maintaining efficient use of the extracted energy;
• better mediating the volatile energy supply and the asynchronous energy demand in edge computing.

Generally speaking, all of the aforementioned micro-energy generators produce AC voltages at the open-circuit condition. The power conditioning circuit should be first designed for adapting to the source characteristics. As shown in Fig. 1, the immediate circuit block after the transducer is called the AC-DC interface circuit. The simplest way to convert an AC voltage into DC is through a diode bridge rectifier[55–58]. Regarding the internal impedance of these sources, they can be classified into two big categories, inductive and capacitive sources. The electromagnetic harvesters are inductive with small internal impedance. Their generated voltage is relatively small (usually from several mV to several V). The piezoelectric harvesters are capacitive with large internal impedance. They give a relatively high voltage output (several V to hundreds of V). The electrostatic ones are also capacitive with an even larger internal impedance. They give the highest voltage output (from tens of V to several kV). Since a diode is a semiconductor device with an almost constant sub-1-V forward voltage drop, the voltage range covered by the piezoelectric case is the easiest to handle, neither too small as the electromagnetic case does, nor too large as the electrostatics case does. The electromagnetic cases usually need a voltage multiplier to passively boost the voltage level for easy utilization. The electrostatic cases usually need better protection to avoid the breakdown under a high voltage beyond the device rating. Moreover, both electromagnetic and piezoelectric sources are self-

▼Table 1. Three types of major electromechanical transducers for kinetic energy harvesting (KEH) and their features

Transducer	Picture	Mechanical Feature	Electrical Feature
Electromagnetic		• Large velocity preferred • Complex assembly • Small- to large-scale systems • Need no contact • Bidirectional force	• Small voltage (mV – V) • Large current (mA – A) • Inductive source • Small output impedance • Self-generation
Piezoelectric		• Large force (hard materials); small force (soft materials) • Simple structure • Small- to middle-scale systems • Need contact • Bidirectional force	• Large voltage (V – kV) • Small current (nA – μA) • Capacitive source • Large output impedance • Self-generation
Electrostatic including triboelectric		• Small displacement (out-of-phase); large displacement (in-phase) • Simple structure • Small-scale system • Need no contact • Unidirectional force	• Very high voltage (kV) • Very small current (nA) • Capacitive source • Very large output impedance • Need a bias-voltage to run (self-generation for triboelectric generator)

generating, while the electrostatic case needs an external source to provide an initial static charge. The external source is used to realize charge separation in a general electrostatic generator[46] Therefore, a general electrostatic harvester requires a more complicated interface circuit compared with electromagnetic and piezoelectric cases. However, in some special electrostatic-like generators, such as the triboelectric[49] and electret[25] ones, where the charge separation is an inherent capability due to the material property. For these systems, the interface circuits can be simpler without using an external source.

Like most practical electric power sources, a KEH source usually has a maximum power point when the load impedance is at a value between the extremely short-circuit and open-circuit conditions. Besides the detailed technical solutions to the very low voltage in the electromagnetic case or very high voltage in the electrostatic case, more studies focused on the maximum harvested power issue. The most straight-forward investigations considered the resistive matching since harvesting energy from a source more or less brings in some damping effect[16 – 17]. The resistive load was emulated using an energy-dissipative resistor in some early studies[59 – 60], and later using a DC-DC buck-boost converter in some later studies toward practical applications[61]. On the other hand, it was proven that the dynamic effect of a bridge rectifier is different from a resistive load[16]. It is slightly capacitive in the piezoelectric case[17] and slightly inductive in the electromagnetic case[58]. No matter for the pure resistive load or those with the slight reactive component, the power optimization can be realized by implementing an additional maximum power point tracking (MPPT) module to tune the duty cycle of the DC-DC converter, which usually corresponds to a specific one-dimensional impedance trajectory, toward the optimal value[23, 55 – 56, 61].

The term impedance matching is usually referred to in KEH technology to emphasize the importance of load tuning. Different from the MPPT concept, which chases the optimal point on a specific one-dimensional trajectory on the two-dimensional impedance plane, the impedance matching technology seeks the global maximum in the entire two-dimensional complex impedance plane, which is formed by the resistive and reactive components[62]. The maximum power transfer theorem is a fundamental concept in circuit analysis; however, there were still some studies that only qualitatively quoted such a concept without quantitative analysis. More studies discussing conjugate impedance matching were conducted for piezoelectric KEH systems[23, 63 – 64]. For the electromagnetic case, the air coil usually gives small inductance[65]. The inductive reactance is much lower than the resistance; therefore, the electromagnetic case usually needs resistive matching. For the electrostatic case, the capacitance is usually extremely small[46]. It produces a large capacitive reactance, which is hard to realize a conjugate matching.

Theoretical studies discussed the impedance matching using linear reactive components, whose values are too large to be put in practical use[66 – 67]. The non-dissipative or less-dissipative impedance matching has been realized using the so-called synchronized switch harvesting technology, which is implemented by using modern switched-mode power electronics. Given the capacitive input impedance of piezoelectric transducer, the synchronous electric charge extraction (SECE) [68] and synchronized switch harvesting on inductor (SSHI)[69] were proposed. The synchronized switch technology can produce a matched or nearly-matched inductive load in a semi-passive and energy-efficient way; therefore, they can enhance the harvesting capability by several folds under the same excitation condition. These switched-mode circuit solutions have stimulated a large batch of following studies[11, 41]. Since the interface design in piezoelectric KEH has such a significant effect, the synchronized switch technology has also been utilized in electromagnetic[70 – 71], and triboelectric (electrostatic) cases[72 – 73] for boosting the harvesting capability.

The KEH technology is designed to replace the large battery storage in some applications. However, this does not mean that the KEH systems have no energy storage devices. Because the input power may be unstable in the KEH-powered system, a relatively small storage device is needed as an energy buffer or filter to improve the reliability in operation. In the previous studies, it was found that the super-capacitors have higher power density and longer lifetime than chemical batteries. Therefore, the super-capacitors are more suitable to provide energy buffers in a KEH system[74].

Before connecting to a digital circuit, the DC storage voltage needs to be regulated to a specific logical voltage level. We must choose a suitable regulator according to the characteristics of every specific KEH source. For example, piezoelectric transducers provide a relatively high voltage output; therefore, the buck converter is usually used for voltage regulation of piezoelectric systems, while the boost converter is mostly used in electromagnetic systems. LTC3588 (Linear Technology Co.) is the most widely used DC-DC regulator integrated circuit (IC) in piezoelectric KEH[75]. Different from the conventional pulse-width modulation (PWM) driven DC-DC converter, LTC-3588 works in Burst Mode (a registered trademark of Linear Technology Corporation), which provides high efficiency at light loads. In the LTC3588, there is an internal undervoltage locking (UVLO) threshold, which is fixed at 5 V (LTC3588-1) or 16 V (LTC3588-2). Only by carefully selecting the appropriate storage capacitor can a good trade-off be made between larger energy storage capacity and rapid charging response. Because the LTC3588 lacks a storage-level indicating signal, to better monitor and manage the stored energy, we often need to add some additional power management circuit design to ensure the energy build-up process[76 – 77]. Such a storage-level indicating signal had better be programmable according to the software scheduling. In some other commercial ICs, e.g., BQ25505 (Texas Instrument Co.)[78], there is a user-defined battery-good indicator, whose threshold can be adjusted offline with a resistor network.

3 KEH-IOT

Given the fluctuating feature of most kinetic energy sources as well as the scarce power output capability, the available energy from a kinetic energy harvester might be unstable and sometimes unpredictable. When building a KEH-IoT system based on these KEH sources, power failures are very likely to happen from time to time. The sensing, computing, and communication tasks carried out by a KEH-IoT system must take sufficient consideration of such limitations and fluctuations. In other words, these battery-free devices are fundamentally different from most conventional computing systems because they violate one of the most basic computing assumptions—a stable power supply[79]. Therefore, building an organic KEH-IoT system can neither easily replace the battery with an energy harvester nor take an IoT node simply as an equivalent constant resistive load. Exploring the synergy among the mechanical, electrical, and cyber parts is necessary for a comprehensive co-design. To build the cyber part of a KEH-IoT system, one has to know several aspects about the emerging battery-free computing technology, i.e., energy-aware operations, computing modes, and useful development platforms.

3.1 Energy-Neutral and Power-Neutral Operations

In the last decade, tremendous efforts have been made to cope with KEH dynamics and achieve a demand-supply balance. The most commonly adopted model for energy utilization is the energy-neutral operation. In such an operation, we use relatively large energy storage for smoothing out the temporally fluctuating dynamics from both energy supply and load consumption. Another alternative model is power-neutral operation. In this operation model, the computational demand is instantaneously adapted to the harvested power, by which the need for large energy storage is eliminated. Only a small energy buffer is needed for a power-neutral system.

1) Energy-neutral operation: The idea of the energy-neutral operation is to decouple the high-frequency dynamics of the

ambient energy source and power consumption of the IoT load, such that the energy supply and demand can be balanced over a long period. Neglecting the power dissipation during conversion, the energy relation within a period T can be formulated as follows:

$$E(0) + \int_0^T P_h(t)\mathrm{d}t = E(T) + \int_0^T P_c(t)\mathrm{d}t, \quad (1)$$

where $P_h(t)$ and $P_c(t)$ are the instantaneous harvested power and consumed power at time t; $E(0)$ and $E(T)$ are the stored energy in the zero and T instants, respectively. Since E_0 and E_T are finite, when T approaches infinite or a sufficiently large number, the energy-neutrality is achieved[80], i.e.,

$$\int_0^\infty P_h(t)\mathrm{d}t = \int_0^\infty P_c(t)\mathrm{d}t. \quad (2)$$

This concept of energy-neutral operation has been extensively accepted by many KEH-IoT designers[81]. For example, Trinity[82] is a self-sustaining and self-contained indoor sensing system, which is powered by airflow-induced vibration. By adding an energy storage device with suitable capacity, it can smooth the short-term energy variations between supply and demand. Without experiencing a power outage over a reasonable period T, the system might "look like" a battery-powered system. It can perform continuous wind speed and temperature monitoring and wireless communications. In addition, several hardware and software synergistic approaches have been proposed to improve the average power generation $\overline{P}_h$ or reduce the average power consumption $\overline{P}_c$, such as the dynamic energy burst scaling technology proposed in Refs. [7] and [83]. This technology uses a simple hardware interface consisting of only a few digital inputs. It allows the system to dynamically adjust the supply voltage according to the needs in operation to minimize the energy consumption. Thus, the system using this technology can operate efficiently with smaller energy storage, although in some intervals, the harvested power is much lower than the minimum power requirement of the load.

2) Power-neutral operation: Different from the energy-neutral operation, the power-neutral operation adaptively modulates the instantaneous power consumption to follow the dynamic variation of harvested power; thereby, the required energy storage capacity can be largely reduced. A small energy buffer, such as a μF-level capacitor, is sufficient to support the "once come, immediately serve" operation. Such a concept can mathematically express by taking T as an infinitesimally small number. When $T \rightarrow 0$, the power relation in Eq. (1) can be simplified by differentiating the both sides, such that we can obtain[80]

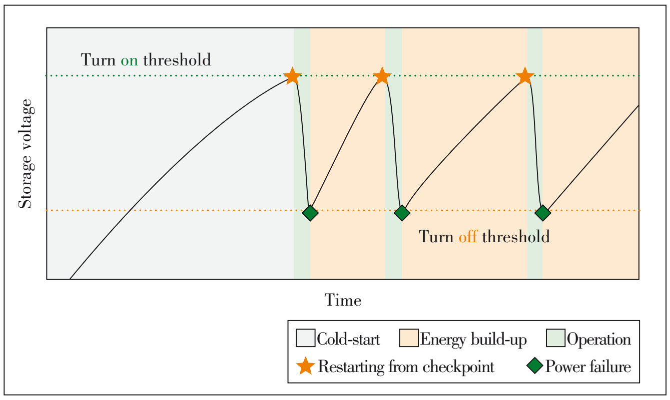
$$P_h(t) = P_c(t). \quad (3)$$

This equation implies that an instantaneous and timely supply demand balance should be implemented in a power-neutral system. Otherwise, if the application requirement varies independently of the harvested power, it might cause a waste of harvested power in some good-harvest periods or degradation of system performance, or even crash in some other bad-crop periods.

In order to satisfy Eq. (3), the power-neutral system must have a more flexible hardware and/or software strategy according to the stringent energy requirement. It can be carried out by moderating its computing tasks using various controls provided by the digital hardware[81]. For example, Hibernus[84–85] achieves a power-neutral behavior on an advanced computing platform. By controlling the central processing unit (CPU) frequency and the number of active cores, Hibernus can modulate the power consumption in real time to match the harvesting dynamics. Compared with the energy-neutral KEH-IoT systems, the power-neutral ones remove the large energy storage unit and its associating charging, monitoring, and conversion circuitry, and accordingly reduce the hardware complexity and improve the energy efficiency.

3.2 Intermittent Computing

Energy-neutral and power-neutral operations only describe the energy service condition of a KEH-IoT system. Each target can be realized by utilizing different software or hardware strategies. Intermittent computing is one of the most extensively studied solutions that ensure reliable and sustainable computing under unpredictable power failures. The working principle of intermittent computing is illustrated in **Fig. 3**. During the intermittent computing execution, the CPU is activated whenever the storage voltage exceeds the turn-on threshold; it is shut down when the storage voltage is below the turn-off threshold. Therefore, the energy build-up periods and computing periods appear alternatively. By separating the computational progress, an intermittent computing system allows long-running applications to progress incrementally under fluctuat-



▲Figure 3. Energy picture during intermittent computing. The energy availability depends on environmental conditions and sometimes also the loading effect. Intermittent execution is a side-effect strategy to cope with this battery-free model, where the blackout periods separating the bursts of execution are unknown

ing or scarce energy conditions. In recent years, intermittent computing has attracted much attention in several related areas, such as programming compiler, hardware-software co-design, and non-volatile technique.

From the typical operation picture of intermittent computing shown in Fig. 3, the turning points marked by red pentagrams and green diamonds represent the energy-aware state checkpointing. When a power outage is imminent, a snapshot of the system states, including the program counter, processor registers, static random access memory (SRAM) contents, etc., is immediately saved in the non-volatile memory (e.g., flash memory, ferroelectric random access memory (RAM), magnetoresistive RAM). During the next power burst, the system reboots and restores the states from the stored checkpoint such that program execution resumes. As a result, long-running programs execute gradually in small increments once the accumulated energy is sufficient[86]. Checkpointing technology has been extensively employed in recent intermittent computing systems. For example, Mementos[87] supports instrument programs with energy checks in the compiling stage. It provides automatic state checkpointing and recovery in runtime. Ref. [88] implemented a battery-free Game Boy with a just-in-time differential checkpointing scheme. It can efficiently preserve game progress despite power failures.

3.3 Development Platforms

Designing a KEH-IoT system from scratch is time-consuming, costly, and leaves little room for error[89–90]. In particular, one should be good at all aspects from mechanical structure designs, to power conditioning circuits, to embedded hardware and software. In real-world deployments, it has to not only adapt to various ambient kinetic sources, such as intermittent vibration of bridges, transient human motion actions, or continuous wind excitation. It must also meet the needs of actual IoT end-users for different customized functions, including sensing, computing, and communication. The design of a practical KEH system, even the simplest one, covers the domain knowledge of mechanical engineering, electrical engineering, and computer engineering. It is desirable to divide the design tasks into their individual domain by taking a "modular way of thinking". However, decoupling by taking simple abstraction usually results in oversimplification and misinterpretation of some practical issues. Most existing studies only demonstrated their performance in one, or at most two, domains. Few have offered a holistic perspective regarding all mechanical, electrical, and cyber considerations, let alone some studies that have also involved materials scientists, civil engineers, biomedical engineers, etc. Building a development platform or test-bed of the KEH-IoT studies is beneficial and important for uniting people from different disciplines. Such infrastructure might lead to the growth and thriving of all related research and development communities[89].

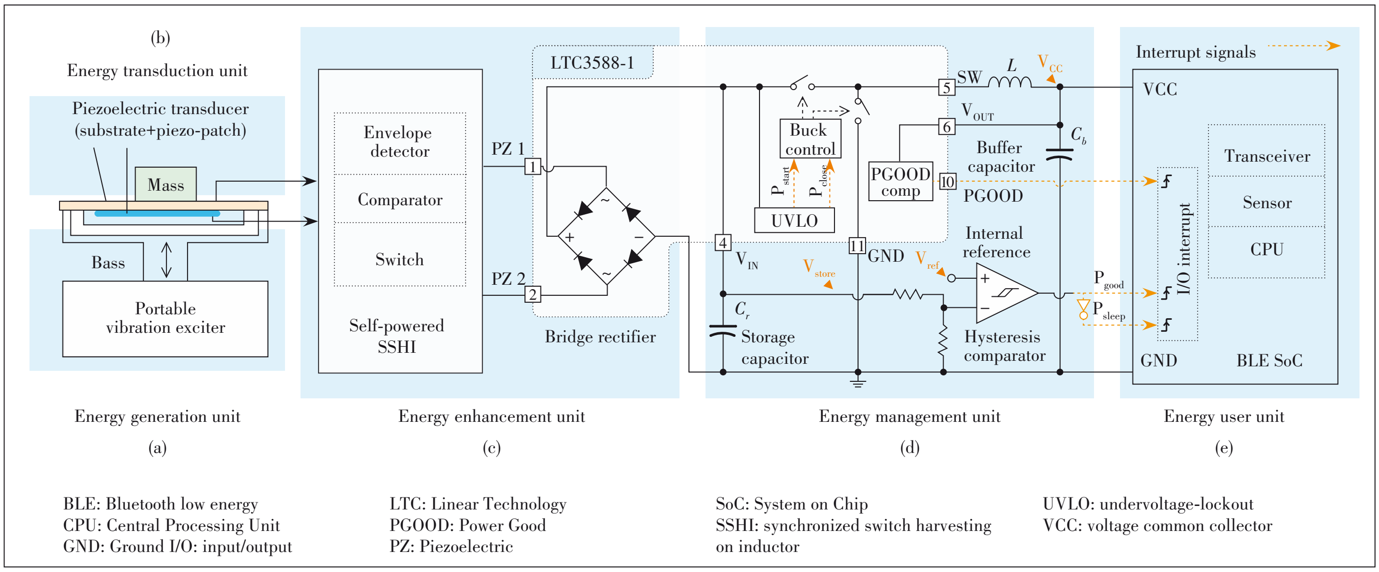
The wireless identification and sensing platform (WISP)[91] has been developed and become a popular platform for the research of battery-free IoT systems; however, it only supports RF energy harvesting devices. Flicker[92] is a more versatile battery-free IoT platform. It supports solar, RF, and kinetic energy sources, as well as a variety of communication peripherals. For KEH, Flicker has fully adopted a typical commercialized KEH specific regulator LTC3588[75, 93], which was designed by Linear Technology Co. ten years ago. The development tool eZ430-RF2500[94], which was released in 2007 by Texas Instrument Co., is one of the earliest electronic platforms designed for energy harvesting applications.

A vibration-power sensing node (ViPSN)[77] is the first open-source battery-free IoT platform specified for KEH. It offers all mechanical, electrical, and cyber parts for an efficient demonstration. The major modules are replaceable and extensible toward rapid prototyping and customization of KEH-IoT systems under different excitation conditions and different application scenarios. More importantly, owing to the enhanced energy management unit, which is developed based on the commercialized LTC3588, an energy build-up phase is inserted between the cold-start and normal operation phases; therefore, a reliable and robust computation is reinforced. ViPSN can efficiently and robustly operate under various kinetic excitations, such as harmonic, intermittent, or transient vibrations. It also supports many kinetic energy transducers, such as piezoelectric cantilever[77], bistable electromagnetic switch[95–97], and triboelectric generator[98]. The mechanical computer-aided design (CAD) model, circuit schematics and printed circuit board (PCB) layout, and fundamental firmware codes are all open-source by the Mechatronics and Energy Transformation Laboratory (METAL) of ShanghaiTech University[3]. **Fig. 4** shows the hardware architecture of ViPSN. It provides all necessary modules from a small vibration generator to Bluetooth low energy (BLE) user unit. It can be regarded as an embodiment of the block diagram shown in Fig. 1. Any peripheral module within the specific energy constraint, such as a low-power sensor, can be added to the KEH-IoT system under this framework for rapid prototyping and efficient customization.

4 Applications

A lot of fundamental and engineering issues as well as possible application designs of KEH[9, 44] and battery-free IoT[12] have been discussed in the related research communities during the last decade. On the other hand, KEH-IoT systems have also attracted extensive attention from the industry. There are several scenarios where KEH technologies can significantly

3. https://github.com/METAL-ShanghaiTech/ViPSN



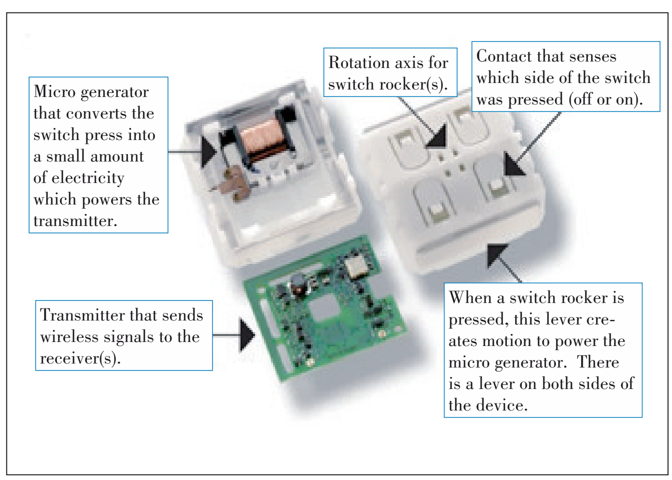
▲Figure 4. ViPSN hardware architecture[77]

enhance the system's performances in terms of less or free maintenance, better information acquisition, lower cost, and environmental friendliness.

First, KEH-IoT systems are the most necessary in applications where the IoT devices need to be deployed in the hard-to-reach or too-far-to-reach areas. For example, Perpetuum Ltd. [99] produced a KEH-based train monitoring system. It can be installed near the wheels for monitoring the vibration conditions of the carriage body to estimate the health condition of the bearings. Since there are many wheels on a train, it is not convenient for frequent maintenance. ReVibe Energy Ltd.[100] and Xidas Ltd.[101] have proposed similar products by harnessing vibration energy from machines, railways, and heavy trucks/vehicles. Enervibe Ltd.[102] manufactures energy harvesters for smart tires and smart shoes. Most of these commercialized harvesters are based on linear electromagnetic harvesters. Each of them can only work in a narrow frequency range.

Second, KEH-IoT systems can be used in applications that require massive deployed IoT nodes (hundreds or even thousands of them). Frequent and massive battery replacement or recharge for all devices are unaffordable. For example, in structural health monitoring, there might be lots of battery-free IoT systems embedded in large structures, such as bridges and highways. The IC solutions are a must toward a low-cost and integrated KEH-IoT system. Besides the big IC companies, such as Analog Devices and Texas Instruments, nowadays, we can also find more and more startups dedicated to the energy harvesting IC technology, ranging from power management IC, such as Nowi Ltd.[103], to the entire system on chip (SoC) solution, such as Atmosic Ltd. [104]. Recently, Renesas Co. has just released its RE Family of 32-bit microcontrollers (MCUs) based on the Silicon on Thin Buried Oxide (SOTB) process technology[105]. These MCUs are equipped with an energy harvesting control circuit inside, which enables further integration toward many possible applications.

Third, KEH-IoT systems are widely adopted in many human-factored applications, where kinetic energy is extracted from human motions, such as walking, running, jumping, and even finger tapping, to power the motion sensing and transmitting tasks, i.e., toward the self-powered and self-sensing wireless motion sensors. A typical case is the motion-powered light switch first developed by EnOcean GmbH[95], whose modules are shown in **Fig. 5**. In such a design, an electromagnetic instantaneous-flipping structure is used for generating energy under finger press excitation. Only one finger press can provide sufficient energy for transmitting several wireless packets. There are several similar products on the market, such as those manufactured by ZF GmbH[106], Alps Alpine Co. [107], Linptech Co.[96], and Chlorop Co.[97]. These battery-free wire-



▲Figure 5. One of the best commercialized KEH-IoT designs, the battery-free wireless light switch developed by EnOcean GmbH[95]

less switches are mostly designed for use in smart home and smart manufacturing scenarios. In addition, Pavegen Ltd.[108] designed a human-powered floor tile, which can harvest footsteps energy to power some environmental monitoring and lighting devices. BinoicPower Ltd.[109] released an energy harvesting knee brace to generate electricity from natural walking. The company claimed that, over the course of an hour, walking at a comfortable pace, users wearing a harvester on each leg could generate enough power to charge up to four smartphones over an hour[110]. It is also worth noting that Bionic Power Ltd. and HoverGlide Ltd. are two startups producing suspending backpacks and had two pieces of fundamental research work about energy harvesting from human motions, which were published in the prestigious journals *Science and Nature*[111–113]. Therefore, the spring of technical transfer of KEH technology is very likely to arrive in the coming decade.

5 Concluding Remarks

KEH-powered IoT is an interesting and emerging topic toward an inspiring vision of ubiquitous battery-free IoT systems for better facilitating our living, manufacturing, etc. It can energize "every sand" in our globe and equip them with perceptivity, intelligence, and connectivity. Tremendous research efforts have been made on either KEH technology or battery-free IoT during the last two decades. The investigations range from pioneering scientific exploration, rigorous engineering modeling and design, to practical application-level development. If the available ambient power is sufficiently large and steady, the easiest way is to take the "modular way of thinking" and consider the mechanical, electrical, and cyber parts as black boxes, as the designs of many modern engineering products did. However, given the practical constraints on size, low power level, volatile source, etc., those modules are usually mutually influenced. People who design the mechanical structure should also have some ideas about the dynamics of power conditioning circuits. Those who design the power conditioning circuits should also understand the possible behaviors of both the mechanical source and the computing behavior. Therefore, the cross-domain knowledge and cyber-electromechanical synergy are beneficial for marching toward a comprehensive and practical KEH-IoT design.

As the topic of KEH-IoT has attracted people across at less five research fields, it is very difficult to enclose all the related work in this short paper. As this paper has cited many comprehensive review articles, readers who are interested in any aspects of KEH-IoT can refer to those detailed papers. It is human nature to start work on the solution of an interdisciplinary problem from his/her own domain knowledge. Some people might think we need more advanced materials for power generation; some might think we need a precise mechanical model and excellent design for better understanding and harnessing kinetic energy; some might think power conditioning is the most significant difference between these systems and the battery-powered ones; some might consider the computing difficulties without getting sufficient energy, etc. However, instead of thinking in a one-sided style, we should open our horizons, be humble, and respect other shareholders' opinions, such that we can arrive at inclusive knowledge and holistic solutions toward valuable co-designs and successful products.

Last but not least, energy harvesting is applied research. Although some large-scale systems, such as ocean-wave power generators, are also called energy harvesting, the majority of studies under this umbrella are about small-scale devices. Given its immediate contribution toward practical applications and productivity enhancement, the information attribute of KEH technology should receive prior attention. It directly enables the devices to function and lets the market healthily run. Power conversion and management unit is necessary, but those issues such as conversion efficiency and harvesting capability are less urgent compared to its functionality. Therefore, the energy attribute comes second. Mechanical designs and modeling are necessary too. However, since only a mechanical structure cannot independently generate useful and transmittable information, mechanical dynamics comes the third. Material scientists have made many pioneering inventions and published many high-impact-factor papers; nevertheless, those new findings usually should go through strict engineering approaches (such as modeling, calibration, standardization and fault test), cost-performance evaluation, etc., before made into a product. Therefore, the material advancement also shares the third urgency, in terms of an immediate contribution to the possible industry. In general, the research and investment strategies on the KEH-IoT technology should closely follow the level of productivity and, at the same time, keep a good balance between application development and fundamental research.

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