Mechanical and Electrical Energy Buffer-release Mechanisms for Motion-powered IoT Applications

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Abstract**—The increasing number of distributed Internet of Things (IoT) devices makes the power supply a prominent issue, which limits the extent and lifetime of ubiquitous IoT networks. Mechanical energy harvesting (MEH) technology transforms the local mechanical energy into useful electricity. It provides a solution for the realization of self-sustainable motion-powered IoT applications. Given the volatile feature of most ambient vibrations, energy management methods are necessary for matching the unstable energy supply from the MEH sources and the energy demand of timely IoT tasks. This paper summarizes and analyzes two energy buffer-release mechanisms (EBRM) from mechanical and electrical aspects, respectively, for ensuring the robust operation of motion-powered IoT systems. Rather than emphasizing harvesting more energy from vibrations, as most of the previous studies did, we focus on energy neutrality among the mechanical, electrical, and cyber ingredients. A preset energy release threshold realized in either a mechanical or electrical way ensures the completion of every fundamental atomic task. The necessity of EBRM is demonstrated in three controlled experiments. Only those systems with a mechanical or electrical buffer-release mechanism can operate correctly.**

I. INTRODUCTION

Energy harvesting (EH) is one of the emerging technologies to replace chemical batteries by scavenging the ambient energy from solar radiation [1], microwave under radio frequency (RF) [2], temperature gradient [3], mechanical motions [4], [5], etc. The harvested energy can be used locally to power IoT devices and make them energy self-sufficient. Most studies considered how to maximize the harvested power under the same excitation. The EH module was often regarded as a substitutive power supply and used in more or less the same way as the conventional batteries. However, further studies have shown that there are more issues to match the energy dynamics of both sides of the EH source and IoT load. More attention needs to be paid to the synergistic designs toward an organic integration of the mechanical, electrical, and cyber ingredients toward the energy-neutral operation.

Among the aforementioned ambient sources, ambient mechanical energy is extensively found in human or machine motions. Most of the mechanical sources also coexist in the scenarios, where IoT functions, such as motion sensing, are needed [6]. Therefore, the motion-powered IoT application is considered a good coincidence where the ambient energy supply meets the information demand. The previous studies of kinetic energy harvesting systems tended to optimize the system by improving the performance of either the mechanical, electrical, or cyber designs. They provided a solid foundation for the development of motion-powered IoT applications by improving the harvesting efficiency [7], [8], reducing the influence of load variation [9], and implementing the intermittent computing program [10]. However, these studies put much more emphasis on either the EH source side or the application side. Less attention was attracted to considering how to make a balance between energy supply and information demand toward a robust and reliable application up to now [11], in particular, in the mechanical dynamics and circuits and systems communities.

Given that the source power from many mechanical EH sources is weak, the trickling energy flow must be properly managed before meeting the timely requirement of the load device. This paper systematically summarizes the two possible power management schemes, or more specifically, the energy buffer-release mechanisms (EBRM), in either the mechanical or electrical way, in order to ensure the correct operation of the self-powered IoT applications. Both the electrical and mechanical EBRMs are conceptually discussed and experimentally validated with some real motion-powered IoT devices. In particular, since the self-powered IoT systems using other EH sources are only applicable by using electrical EBRM, the uniqueness of mechanical EBRM for motion-powered systems is emphasized in this paper.

II. MOTION-POWERED IOT DEVICE

Fig. 1 shows the overview of a motion-powered IoT device. A mechanical EH module is used for collecting mechanical energy from everyday motions. A circuit module converts the ac energy into dc form and carries out some power management actions. The data transmission unit transmits the information to the Internet through a standard IoT protocol, such as BLE or LoRa. Although the transducers act a key role in connecting the mechanical and electrical domains; a comprehensive co-design must be carried out to handle all the energy flow and its power dynamics among the mechanical energy source, electromechanical transducer, power management scheme, and IoT load with dynamic power demand.

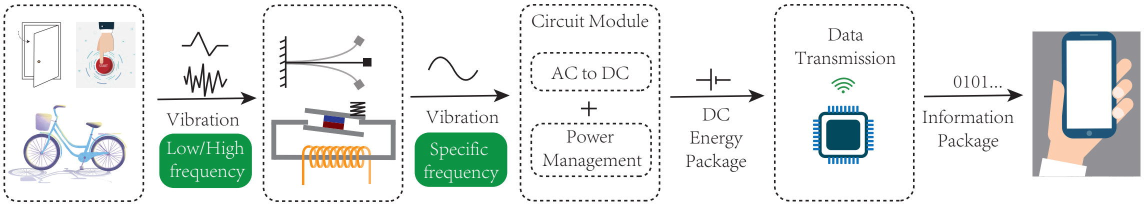

Fig. 1. Overview of a motion-powered IoT device.

A. Mechanical Energy Harvester

A mechanical energy harvester (MEH) is composed of a mechanical structure, which moves in response to external excitation, and an electromechanical transducer, which transforms the energy into the electrical form. A linear MEH device can only harvest energy in a very narrow bandwidth. To match various source frequencies of many ambient vibrations, the frequency up-conversion mechanisms are extensively investigated [12]. Existing frequency up-conversion methods include impact-based, snap-through, and plucking designs. In previous studies, most of them were studied under kinetic, i.e., continuously moving, scenarios. Recent studies have shown that the MEH mechanism has a unique quasi-static bistable operation mode [4], [13], which is not experienced in those EH devices based on other transduction mechanisms. Such a quasi-static operation of bistable structures facilitates the realization of EBRM in the mechanical domain, whose principle is discussed in detail in Section III.

B. Energy Conversion and Management Circuit

In a general low-power EH system, a power conditioning circuit module is necessary for two tasks – converting the ac input into a dcdigital voltage and carrying out EBRM to ensure the nonstop operation within every atomic sensing, computing, or communication task. The second task can be replaced in some cases if a mechanical EBRM is implemented.

C. IoT Node Device

Intermittent computing, which is extensively discussed in the IoT community in recent years [11], is a must considering the low-level and unstable power supply in almost all EH scenarios. Yet, an atomic task is considered the minimum indivisible software unit that cannot be executed intermittently. For example, a packet transmission cannot be interrupted in the middle of a service routine, otherwise, the transmission fails.

D. Supply and Demand Balancing

All the mechanical, electrical, and cyber parts are tangible ingredients for building a motion-powered IoT device. We still need an intangible principle to integrate them into a successful and reliable co-design. It is an ultimate goal for applicable and real-world designs. Yet, the state-of-the-art designs are far from mature on this track. Up to this point, most available devices are open-loop-style designs. They use EBRM units to ensure the reliable operation of every atomic task. The mechanism to ensure the timely delivery of a task was unclear. Therefore, EBRM only ensures that most harvested energy is effectively used, whether it is properly used to meet the information demand needs further and in-depth investigations in the future.

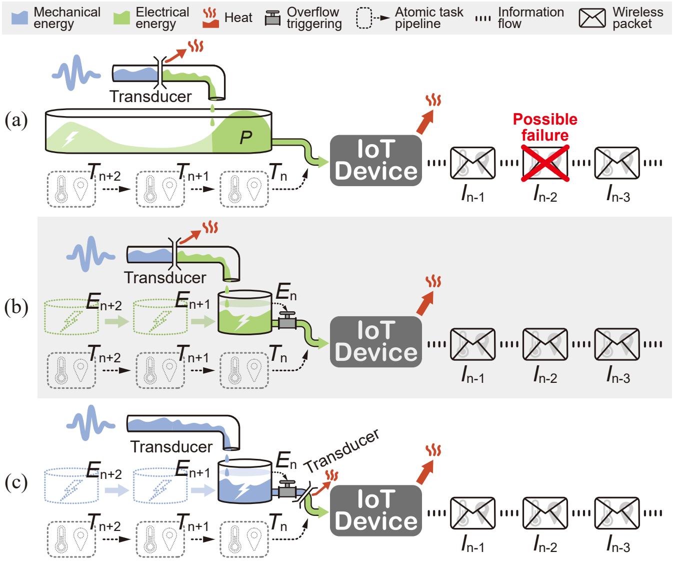

Fig. 2. Energy to information (E-to-I) generation processes illustrating the effect of EBRM. (a) A direct process without EBRM. (b) A process with electrical EBRM. (c) A process with mechanical EBRM.

III. ENERGY BUFFER-RELEASE MECHANISMS (EBRM)

The ambient EH sources are usually characterized as low-power and fluctuating. It was realized, at its early development stage, that the motion-powered IoT devices should operate under the so-call *burst mode* [14]. More specifically speaking, the trickling and fluctuating energy flow should be first buffered to a sufficient amount and then released at a sufficiently high power level, such that to meet both the energy and power requirements of a specific IoT load and function. Yet, the co-design is hard to carry forward without an interdisciplinary consideration of both the source and load dynamics.

Both the power and energy demands should be met to correctly activate the IoT system on chip (SoC) from the cold start and fulfill every atomic task. Fig. 2 shows the conceptual energy-to-information pictures of three types of systems under different power management schemes.

A. System without EBRM

The first one has no EBRM. The energy is converted from mechanical (blue) to electrical (green) form. It is directly used to drive the scheduled tasks T_n. Only when the maximum power and accumulated power from the source exceeds that of the load demand before finishing an atomic task, can the n^{th} IoT packet I_n be successfully sent out. Otherwise, possible failure is very likely to happen.

B. System with Electrical EBRM

The basic principle of electrical EBRM is similar to that of an under-voltage lockout (UVLO) module. No energy is released until the storage voltage, or equivalently the energy amount, exceeds a specific level. The trickle mechanical energy flow is converted into electrical form immediately and accumulated in the electrical storage device. Once a threshold is attained, the scheduled task can be reliably carried out, as illustrated in Fig. 2(b). The ON and OFF thresholds V_{on} and V_{off} set the maximum available energy of all atomic operations, i.e.,

$$E_0 = E_{e,\text{ON}} - E_{e,\text{OFF}} = \frac{1}{2}C_s(V_{on}^2 - V_{off}^2), \tag{1}$$

where C_s is the storage capacitance. Ref. [15] introduced a low-cost energy management circuit with EBRM for energy-harvesting-powered IoT devices. In this design, either the ON or OFF threshold can be tuned, respectively, for satisfying the IoT tasks with different levels of computational effort.

C. System with Mechanical EBRM

Mechanical EBRM is utilized for many years in the engineering products of battery-free motion-powered switches [16], [17]. Yet, rigorous study was absent until a recent paper, which revealed the quasi-static toggling (QST) procedure of an electromagnetic (EM) harvester [13]. Owing to the instantaneous magnetic pole swapping design, the EM self-powered switch actually carries out the EBRM function in the mechanical domain. Fig. 2(c) illustrates the concept of mechanical EBRM. The energy is buffered in a mechanical storage device, usually a spring. The amount of buffered energy in each round must also satisfy the maximum available energy of all atomic operations, i.e.,

$$E_0 = \eta(E_{m,\text{ON}} - 0) = \frac{1}{2}KX^2, \tag{2}$$

where η is the electromechanical conversion efficiency; $E_{m,\text{ON}}$ is the buffered mechanical energy; K is the spring stiffness; X is the spring deformation at a releasing instant.

IV. IMPLEMENTATION AND EVALUATION

All the aforementioned three types of motion-powered systems are implemented and tested for evaluating the necessity of different ERBM designs. Fig. 3 shows the hardware setups (row 1), block diagrams (row 2), conceptual energy pictures (row 3), and experimental waveform (row 4) in the three cases without EBRM (column a), with electrical EBRM (column b), and with mechanical EBRM (column c).

A. Case 1: System without EBRM

In this case, the output electrodes of a piezoelectric structure are directly connected to a circuit for ac-dc conversion and voltage regulation. In this experiment using neither electrical nor mechanical EBRMs, the IoT SoC is hard to start up with a trickling energy source. To successfully carry out an atomic task from a zero energy condition, two criteria–*sufficient drive power capability* and *sufficient buffered energy* must be simultaneously satisfied. Fig. 3(a3) depicts the conceptual energy picture in this case. Without the hysteresis for system-off buffering and system-on release, the trickling income current from the EH source all leaks in the SoC before it passes the most power-hungry period of a startup process. Let alone the successful operation of a basic computing task. Only when the source power is sufficiently large, the SoC can be successfully started up and fulfill a task requiring a specific amount of energy. The experimental waveform, which is shown in Fig. 3(a4), also demonstrates that the buffered energy is stuck at a certain level which is not sufficient to start up the electronic system. The maximum start-up power, in this case, is about 1 mA, which is larger than that the EH source in use can supply.

B. Case 2: System with Electrical EBRM

The second type of system using electrical EBRM is the most extensively adopted scheme for powering low-power electronics with an ultra-low-power EH source. Some commercial IC products, such as LTC-3588 (by Analog Devices Inc.) and BQ25505 (by Texas Instruments Inc.), also implemented the hysteresis between the undervoltage and overvoltage levels for ensuring proper operations. A UVLO ensures an extremely low current leakage at the power-off condition, i.e., the output impedance is extremely high. Once the storage voltage exceeds the threshold, it rapidly increases the current drive capability, i.e., the output impedance becomes very low. In this study, we use a power conditioning circuit, which encapsulates the ac-dc rectifier, electrical EBRM, and voltage regulator, to condition the energy harvested from a piezoelectric structure and use them to power a BLE SoC, as shown in Fig. 3(b1). By inserting an electrical EBRM module, the energy buffering-release cycles and IoT tasks can be smoothly carried out. An electrical EBRM cycle is illustrated by the solid (buffering) and dashed (release) lines in Fig. 3(b3). The same amount of energy E_0, which is the difference between the on $E_{e,\text{ON}}$ and off $E_{e,\text{OFF}}$ levels, can be reliably provided in each round of intermittent operation. Since all the income energy is accumulated and buffered in the storage capacitor C_s, the input power fluctuation can be smoothed out; the sudden demands of output current can be much better satisfied.

C. Case 3: System with Mechanical EBRM

Among all the possible EH sources, a mechanical source is likely the only one that can easily retain stable potential energy, which can be rapidly transformed into electricity. By designing a mechanical EBRM, we can ensure the robust operation of a motion-powered IoT device, even without an

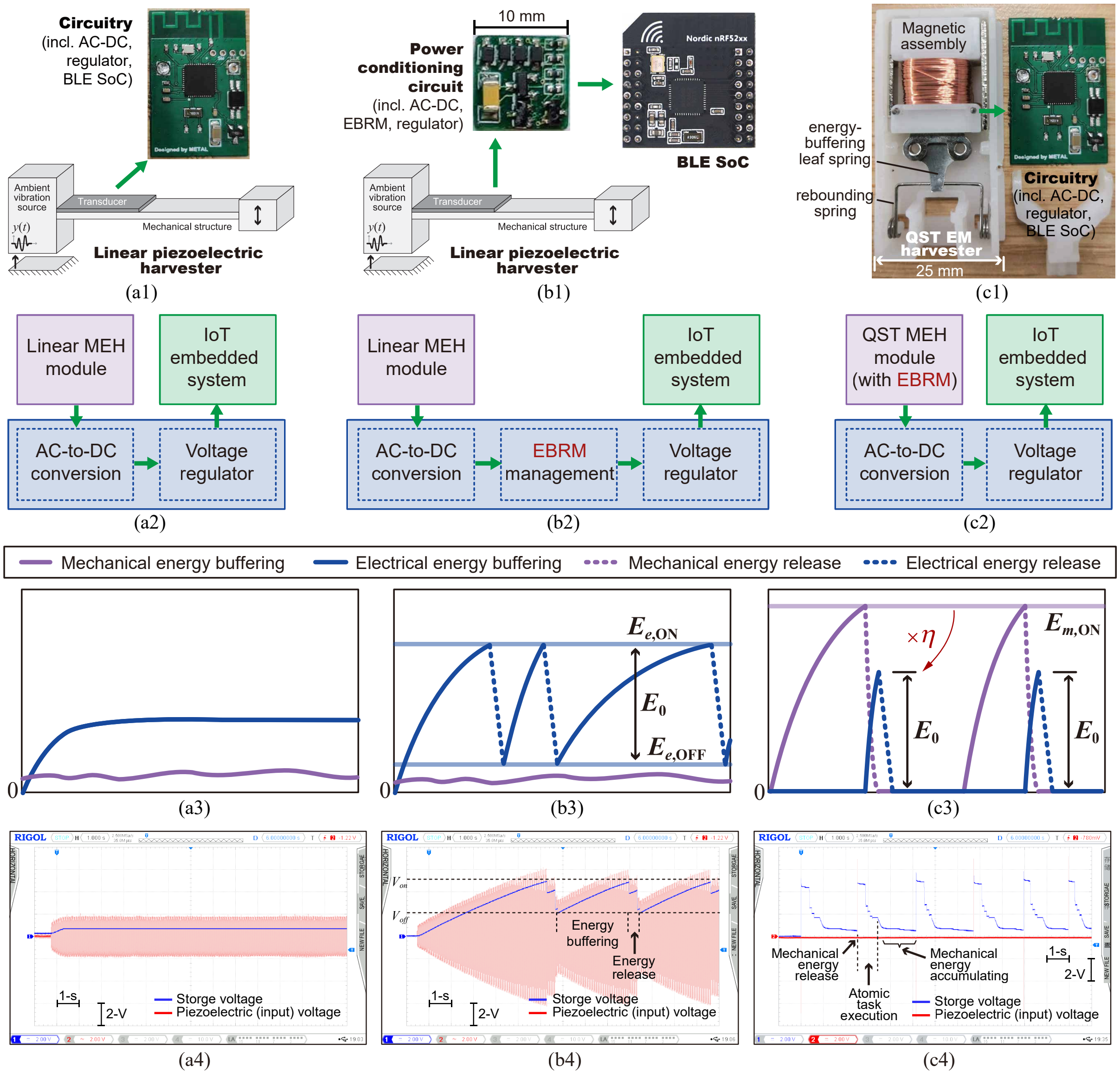

Fig. 3. Configurations and energy pictures of three types of systems. (a1-a4) No EBRM. (b1-b4) With electrical EBRM [15] (c1-c4) With mechanical EBRM [13]. (a1-c1) Hardware setups. (a2-c2) Block diagrams. (a3-c3) Conceptual pictures showing the energy dynamics. (a4-c4) Experimental waveform.

electrical EBRM. In this study, we use a QST MEH module and the same PCB circuit used in the first case to test the effect of the mechanical EBRM. The hardware setup is shown in Fig. 3(c1). In the bistable mechanical design with EBRM capability, the amount of buffered energy is decided by the depth of the bistable wells and the energy-buffering spring [13]. In this paper, this amount of buffered energy is denoted as $E_{m,\mathrm{ON}}$. The available electrical energy E_0 after a mechanical release is formulated in (2) and illustrated in Fig. 3(c3). For an EM harvester, more intensive energy transduction happens alone with a high-velocity movement, the mechanical energy release (purple dashed) and electrical energy buffering (blue solid) simultaneously and almost instantly happen. Given that the instantly transformed power is sufficiently large to cross the maximum power demand at startup; also, the buffered energy amount is sufficient to drive an atomic task, the QST-based IoT device can robustly operate. The experimental waveform shown in Fig. 3(c4) validates the correct operation.

V. CONCLUSION

This paper introduced two electrical and mechanical ways to realize the energy buffering-release mechanism (EBRM) for the reliable design of a motion-powered IoT device. The major obstacles against a direct source-load connection are the large power demand at startup and the specific energy demand of an atomic task. To solve these issues, energy accumulation can be realized in either the mechanical or electrical domain. The comparative experiments with the three systems show that the EBRM module, no matter in mechanical or electrical form, is necessary for constructing a reliable and robust motion-powered IoT system.

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