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Exploring the Magnetic Plucking Motion towards A Transient-Motion-Powered IoT Sensor Node

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ABSTRACT

This paper introduces a transient-motion-powered IoT sensor node, which is called ViPSN-E. It can carry out motion detection and wireless communication by making good use of the energy harvested from an instantaneous unidirectional motion. The mechanical energy harvester is composed of a piezoelectric cantilever and a pair of repelling magnets, which realize the plucking excitation under low-speed movement. Different from the system under periodic excitation, whose energy can be continuously accumulated over time, a single plucking motion only inputs a limited amount of energy to the system. An asymmetric structure is designed for identifying the open-door and close-door paths based on the differences between the amounts of their harvested energy. The working mechanism of the magnetic plucking motion is analyzed considering the potential wells variation during the open-door and close-door movements. On the other hand, efficient conversion and utilization of the limited amount of energy are challenging. The prototyped ViPSN-E includes an efficient power management unit, therefore can make good use of the energy harvested from each transient plucking motion. Only one plucking can fulfill the tasks of temperature sensing, motion direction detection, and several rounds of wireless transmissions. The harvested energy and consumption of the IoT node are analyzed to validate the feasibility of this design. The proposed ViPSN-E provides valuable guidance towards the design of self-powered ubiquitous motion-sensing systems.

Keywords: Kinetic energy harvesting, piezoelectric, magnetic plucking, Internet of Things (IoT), transient power

1. INTRODUCTION

Given the rapid development of the Internet of Things (IoT) technology, ubiquitous sensing and computing are going to penetrate every area of human life in the coming decade. One of the most extensively expected applications is ubiquitous motion detection. With the vision of building an Internet of Moving Things (IoMT), there will be tons of movement detectors installed in our surroundings in the future. If all IoT devices are still powered by chemical batteries, it may cost a lot for frequent battery replacement or recharging.[1] Harvesting energy from the environment provides unprecedented convenience and opportunity to extend the applications' lifetime and reduce their maintenance cost, in particular, for extensively deployed and long-lasting motion detectors.[2]

Compared with the solar[3] and radio frequency (RF)[4] powered sensors, the vibration-powered ones do not work depending on illumination and RF received signal strength. It can be installed at any place, where vibrations or mechanical movements exist. For example, everyday activities such as walking can generate approximately 120-270 μW power.[5] Even writing with a pencil, spinning in a swivel chair, and opening a drawer can provide 10-15 μW power.[6] Therefore, researchers have developed different kinds of vibration harvesters, such as shoe insoles for harvesting energy from foot steps[7] and mobile phone chargers integrated in backpacks.[8]

For decades, how to improve the harvesting capability is extensively discussed for vibration energy harvesting under continuous excitation.[9] Tremendous efforts have been taken to broaden the operating bandwidth and harness low-frequency mechanical energy. In particular, plucking motions including mechanical plucking and

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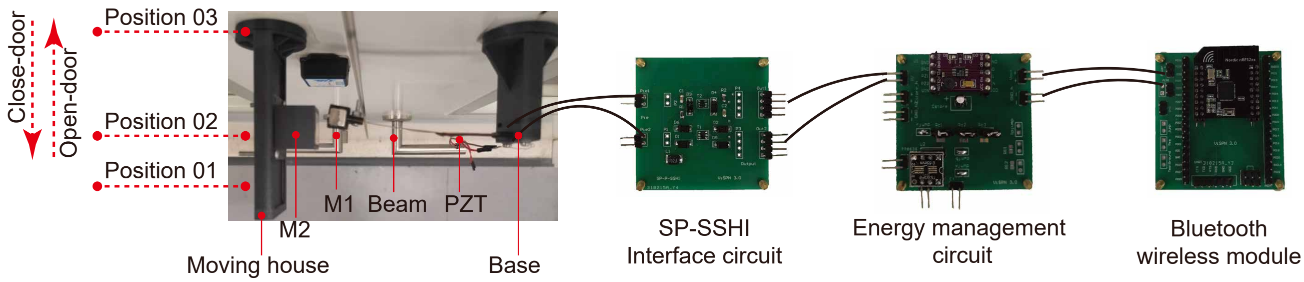

Figure 1. The prototyped ViPSN-E device, which is composed of a piezo-magneto-elastic harvester, a self-power synchronized switch (SP-SSHI) interface circuit, a power management circuit, and a commercial BLE module. In this case, the magnetic plucking harvester is installed on door and door frame for harvesting motion energy and detecting the open-door and close-door actions.

magnetic plucking have attracted much attention towards to implementations of low-frequency energy harvesters. For example, Fang and Liao[10] developed a music-box-like extended rotational mechanical plucking energy harvester. Pillatsch and Yeatman[11] presented a magnetic plucking beam array for harvesting energy form a rotating proof mass. On the other hand, most of the reported vibration-powered IoT applications in literature operate under continuous vibration excitation. For example, Trinity[12] harvests energy from the indoor airflow by using a linear piezoelectric bimorph. A more challenging topic is how to make timely and efficient usage of the limited energy associated with a transient motion such as single plucking or base impulse.

In the previous studies, the plucking mechanism[10,11,13] was investigated for the frequency-up conversion. Most works emphasized the mechanical structure; while their electrical parts were simply linear resistors. On the contrary, most of the previous vibration-powered IoT designs[7,12,14] used simple linear harvesters; the mechanical dynamics has not received sufficient consideration. Few studies went across the boundaries among different disciplines and worked out a synergy among the necessary mechanical, electrical, and cyber parts towards a perfect integrated motion-powered (MP) IoMT device.

In this paper, we propose a transient-motion-powered IoT sensor node, which is named ViPSN-E, based on a cyber-electromechanically synergistic co-design. It is one of the most pioneering designs, which can make full use of a single plucking motion for realizing a self-powered and self-contained IoT application. The dynamics of a single plucking process such as the potential well changing behavior is discussed in detail for revealing its energy transforming mechanism.

2. DESIGN AND WORKING PRINCIPLE

The prototype of ViPSN-E is shown in Figure 1. The system is developed based on ViPSN, a vibration-powered sensor node IoT platform proposed by Li et al.[15] ViPSN is composed of four modules: a source unit for emulating the real-world vibration; an interface circuit for enhancing the harvesting capability and doing the ac-to-dc conversion; an energy management unit to regulate the voltage; and a Bluetooth Low Energy (BLE) user unit to handle the sensing, computing, and communication tasks. In the ViPSN-E design, the vibration emulating source unit is replaced by a piezo-magneto-elastic structure, which is composed of a piezoelectric cantilever and a pair of magnets (M1 and M2 as shown in Figure 1). The repelling magnets are installed on a moving door and its fixed door frame, in order to generate the magnetic plucking excitation under either the transient open-door or close-door movements. A self-powered synchronized switch harvesting on inductor (SP-SSHI) designed is used as the interface circuit[16] and a commercialized voltage regulator is used for generating a constant 3.3 V voltage output for powering digital module. The BLE user unit evaluates the movement direction based on the amount of transformed energy and sends out the information. In order to better explain the working dynamics of the design, three key positions of the moving house are marked out in Figure 1.

The plucking mechanism was studied in literature;[11,13,17–19] yet, most studies focused on its frequency-up conversion under periodically excitation. In this study, we make use of only one plucking movement. In each plucking motion, the beam is bended by a moving magnet. It is released after passing a critical position and

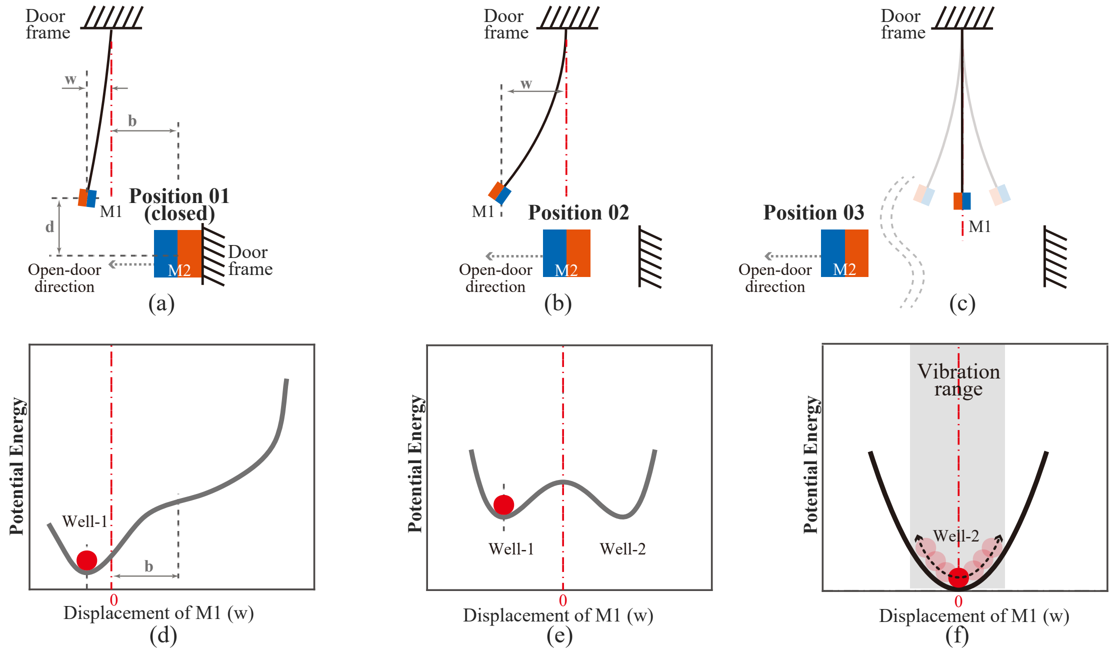

Figure 2. Plucking dynamics under the open-door movement. (a)-(c) Beam positions. (d)-(e) The corresponding potential wells. (a) and (d) Starting point at position 01 with two asymmetric wells. (b) and (e) Intermediate point at position 02 with two symmetric wells. (c) and (f) Final point position 03 ending up with the beam vibration in a (linear) single well.

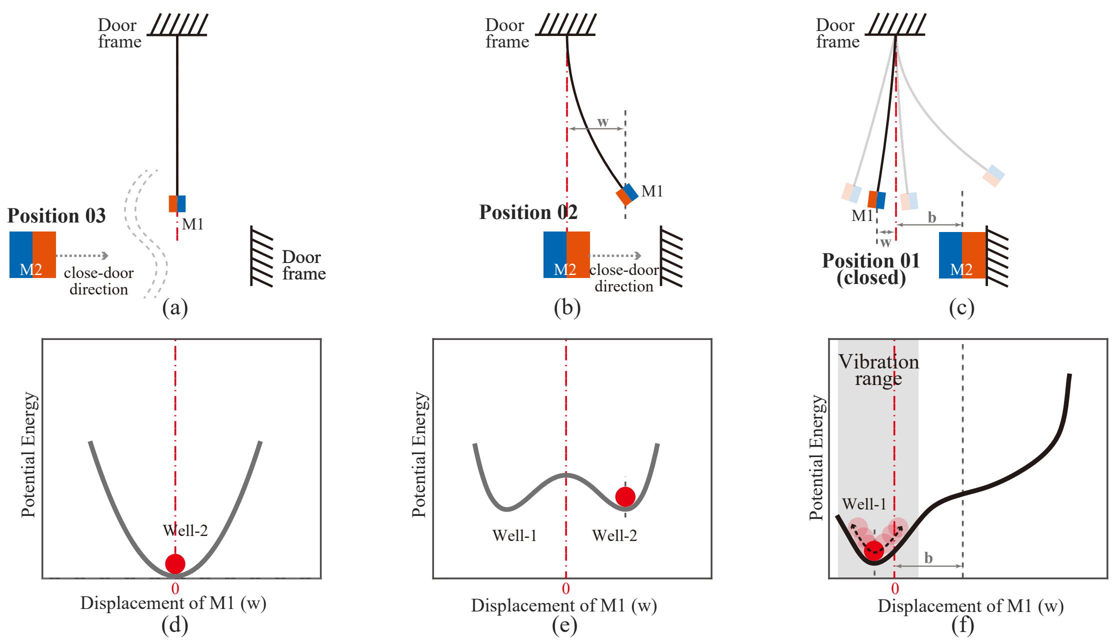

Figure 3. Plucking dynamics under the close-door movement. (a)-(c) Beam positions. (d)-(e) The corresponding potential wells. (a) and (d) Starting point at position 03 with a single well. (b) and (e) Intermediate point at position 02 with symmetric wells. (c) and (f) Final point position 01 ending up with the beam vibration in a deeper well out of the two asymmetric wells.

then starts to oscillate at its resonant frequency until the vibration is damped out. The operating principle of the asymmetric plucking design in ViPSN-E under open-door and close-door movements are illustrated in Figures 2 and 3. As the door magnet moves, the profile of potential energy (sum of the beam elastic and magnetic portions) progressively changes. As shown in Figures 2(d)-(f), in the open-door case, it starts from the asymmetric single well-1, passes through the symmetric double wells condition, and finally ends up with an under-damped oscillation in another single well-2. For the close-door case, it takes the reverse direction and ends up with an oscillation in the asymmetric well-1. Given such an asymmetric design, the vibration after either the open or close movement are different. Such difference results in the different amounts of harvested energy in these two motions, which are utilized to identify the open-door or close-door motions. In general, the final well after the close-door movement is shallower; therefore, the transformed energy by the close-door movement is less.

In this design, the asymmetric plucking design is realized by adjusting the distance between the door magnet and the beam neutral position, i.e., the gap b in Figure 2 and 3. As ViPSN-E should robustly carry out sensing, computing, and wireless communication functions, we must make sure the energy collected during the open-door movement, which gains less energy, is sufficient to energized at least one round of these functions.

3. ENERGY ANALYSIS

The magnetic plucking harvester can be studied with a single-degree-of-freedom (SDOF) vibrator model and an additional plucking force, whose effect is regarded as a nonlinear function of x, distance between masses M1 and M2. The nonlinear dynamic relation between force and displacement can be approximated with a third-order polynomial.[20,21] The total potential energy is expressed as follows:

$$U(x) = \frac{1}{2}(k-\alpha)x^2 + \frac{1}{3}\beta x^3 + \frac{1}{4}\gamma x^4, \tag{1}$$

where α is the coefficient of linear stiffness, β is the asymmetric coefficient, γ is the coefficient of cubic nonlinear stiffness. These three parameters are related to the distance between the beam (vibrating) magnet and the door (driving) magnet.

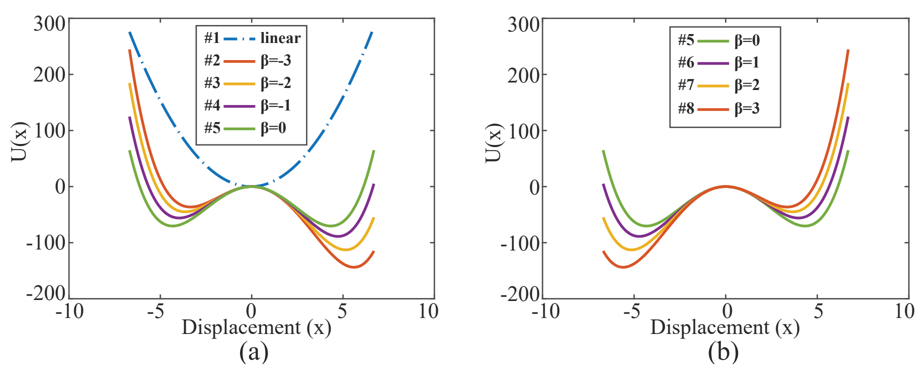

Figure 4. Potential wells profiles under different γ: (a) $\beta \leqslant 0$ cases; (b) $\beta > 0$ cases. ($k-\alpha=-15$, $\gamma=0.8$ in all cases.)

Taking the position of door magnet as zero, the potential wells under different parameter β are shown in Figures 4. When $\beta = 0$, it forms a symmetric double-well bistable structure. As the door magnet moves from position 02 to 01 during the close-door movement, β increases. The two potential wells becomes asymmetric. The potential barrier from right well to left well decreases with a larger number of β. As the depth of the left well increases, while that of the right well decreases, the right well will be finally disappeared. After passing a critical position, the proof mass (vibrating) magnet will drop into the rest single well and oscillate until damped out, as shown in Figure 3(f). When the door magnet moves from position 01 to 02 during the open-door movement, β decreases to a more negative number from zero. In particular, when the door is at position 03, which is far away from the beam magnet, i.e., the door is fully opened, the magnetic force disappears; therefore, the beam magnet exhibit linear under-damped oscillation, as shown in the Figure 2(f).

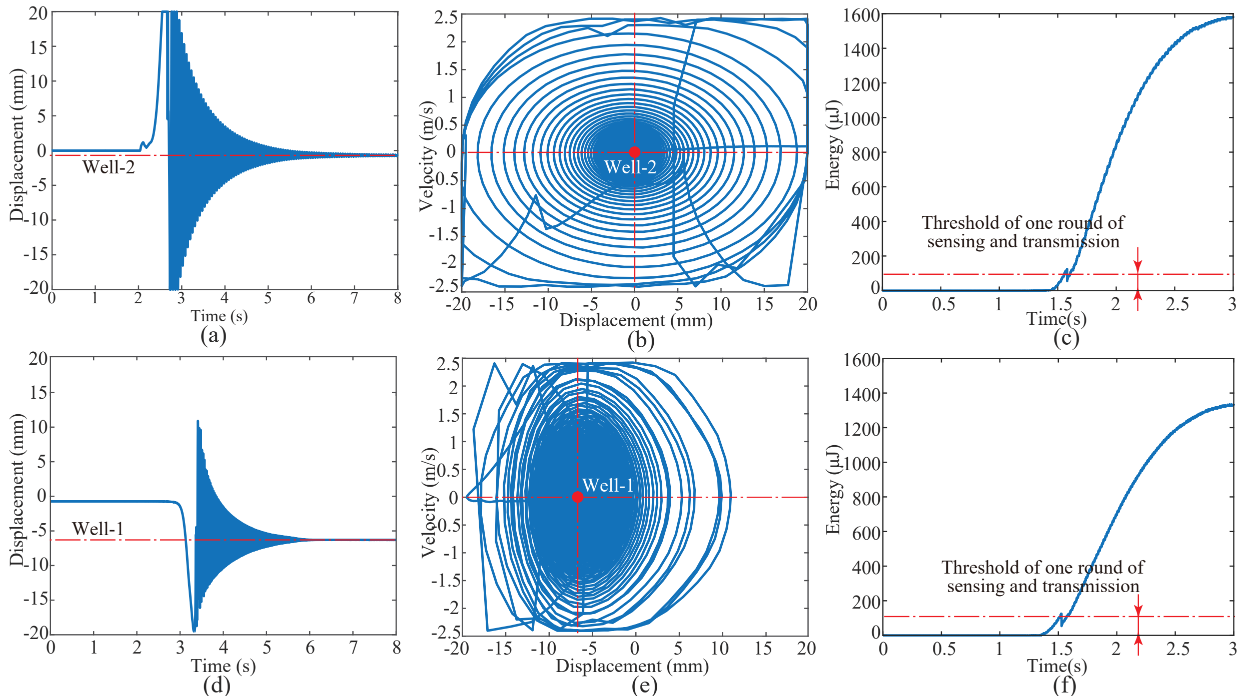

Figure 5. Experimental results. (a)-(c) Open-door characteristics. (d)-(f) Close-door characteristics. (a) and (d) Beam displacements. (b) and (e) Displacement-velocity phase portraits. (c) and (f) Charging history.

Table 1. Power and energy statistics.

Operation	Initialization	Sensing	Transmitting	Sleeping
Peak power (mW)	86.1	8.0	34.3	5.85×10^{-3}
Energy (μJ)	56.8	1.2	42.2	-

In order to realize the plucking motions in both directions, the start and final positions of the door magnet must be in two different potential wells. The door magnet should not be aligned with the fixed end of the beam when the door is at its closed state, i.e., position 01; otherwise, it produces a symmetric double-well configuration, in which the beam magnet has the same possibility to stay in either the left or right well. The depth of potential well is tunable by adjusting the offset between the beam fixed end and the center of door magnet, i.e., parameter b in Figure 2 and 3.

4. IMPLEMENTATION AND ENERGY EVALUATION

The experimental setup of ViPSN-E is shown in Figure 1. The holding frame of this magnetic plucking harvester is manufactured with a 3-D printer. A piezoelectric cantilever is installed at the door frame (fixed). A pair of magnet are installed at the moving door and cantilever free end, respectively. The power and energy statistics of a BLE IoT module as the load are listed in Table 1. At least 100.2 μJ energy needs to be harvested for fulfilling one round of initialization, sensing, and transmitting functions. On the other hand, the final harvested energy in two actions should be different for telling the corresponding motion direction.

Figure 5 shows the dynamics of this plucking harvester, including the beam displacement, displacement-velocity phase trajectory, and harvested energy, under two plucking operations in open-door and close-door directions. In the open-door movement, the harvester is plucked and oscillates in a single linear well-2 as shown in Figure 5(a) and (b). In the close-door case, the harvester finally oscillates in a asymmetric single well-1 as shown in Figure 5(d) and (e). Experimental results in Figures 5(c) and (f) show that during the open-door and close-door motions, ViPSN-E can robustly harvest about 1600 μJ and 1300 μJ of electric energy, respectively. Thanks to the cyber-electromechanical synergy, the energy harvested from a single plucking motion is sufficient to carry out several rounds of motion sensing and wireless communication functions by using this prototyped MP-IoMT device.

5. CONCLUSION

In this paper, we introduced ViPSN-E, a cyber-electromechanical synergistic co-design towards the transient-motion-powered IoMT. A magnetic plucking energy harvester is used to scavenge the energy associated with a transient motion. Through the collaboration between the plucking piezoelectric cantilever and the embedded computing system, the movement information including motion direction can be identified and sent out with a commercial BLE module. The energy harvesting performance can be further optimized by further tuning the mechanical structure parameters, such as depth of potential well and height of potential barrier. The prototyped device were implemented and deployed in real-world scenarios. Experimental results showed that the energy harvested from a single plucking motion is sufficient to carry out several rounds of sensing function and wireless transmission. This study provided valuable guidance for the design and optimization of future MP-IoMT devices.

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