

ViPSN-Pluck: A Transient-Motion-Powered Motion Detector

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Abstract—The emerging energy harvesting technology facilitates the development of ubiquitous and everlasting battery-free motion detectors. This article introduces a robust design of the transient-motion-powered motion detector, which is called ViPSN-pluck. “ViPSN” is the acronym for the vibration-powered sensing node while “pluck” stands for the plucking-motion energy harvester. By using a piezo-magneto-elastic structure, ViPSN-pluck can efficiently harvest energy from a transient motion. By properly making good use of this tiny harvested energy, ViPSN-pluck can effectively carry out motion detection and Bluetooth low-energy (BLE) wireless communication. Given the concurrency of mechanical potential energy precharging and motion detection, the transient-motion plucking energy harvester used in ViPSN-pluck has the merit of high energy reliability. This unique feature is unprecedented in the solar and radio-frequency (RF) energy harvesting cases, which might suffer from energy outages under fluctuating irradiance or RF signal strength, respectively. The working principle of ViPSN-pluck, in particular, the dynamic characteristics of the plucking energy harvester and the energy matching between generation and utilization, are discussed in detail to demonstrate the robustness in operation. The cyber-electromechanical synergy among the mechanical dynamics, power conditioning circuit, and low-power embedded system is highlighted. The design methodology of ViPSN-pluck provides a valuable reference for the developments of future motion-powered Internet of Things devices.

Index Terms—Battery-free Internet of Things (IoT), energy harvesting, motion detector, plucking, ubiquitous sensing.

I. INTRODUCTION

MOTION detection plays an essential role in security surveillance [1], intruder detection [2], occupancy identification [3], activity monitoring [4], smart

building [5], [6], etc. Motion detectors should be economical and robust, such that they can be massively deployed and offer pervasive service to support various smart applications [7]. Existing motion detecting technologies are mostly based on visual [8], [9], infrared [10], mechanical [11], or audio [12] sensors. Some are expensive and require complex installation. Moreover, most of these motion detecting devices are still powered by grid power or chemical batteries. As the number of nodes increases, electrical wiring or battery maintenance costs considerable money and human effort. Therefore, battery-free and maintenance-free solutions are necessary for the ubiquitous and everlasting deployment of massive motion detectors.

Energy harvesting, as an emerging technology in the last two decades, aims to scavenge wasted energy from the ambiance. It provides promising solutions to address the sustainable power supply issue and facilitates the realization of battery-free and maintenance-free Internet of Things (IoT) devices. The battery-free motion-sensing devices powered by ambient solar photovoltaic (PV), radio-frequency (RF), or kinetic energy, have attracted numerous research interests in recent years. For instance, a series of RF-powered passive tags has been built for motion monitoring [13], [14]. Solar-powered smart on/off body sensing devices have been developed to record and infer human activities and interactions [15], [16]. The design of battery-free cameras has been extensively explored by considering the issues from various perspectives, including the harvesting sources [17], wireless communication [18], and system architectures [19], [20].

Like most of the renewable energy sources, the ambient energy sources are volatile, i.e., it often fluctuates with time. Therefore, energy-harvesting-powered IoT devices are remarkably different from their conventional battery-powered counterparts because the variable ambient power supply violates the basic assumption of battery-powered devices—a stable energy supply [21], [22]. The sensing, computing, and communicating tasks in battery-free systems need to be redesigned to better meet with the unstable power supply [23]. It is challenging that, even with some cutting-edge techniques, such as progress checkpointing [24], special debugging tools [25], and finely tuned or reconfigurable power supply strategies [26], energy-harvesting-powered devices are still less reliable than their battery-powered counterparts [27].

In PV, RF, and most kinetic energy harvester (KEH) cases, the harvested power is accumulated or buffered in the electrical domain after energy transduction. On the other hand, given its

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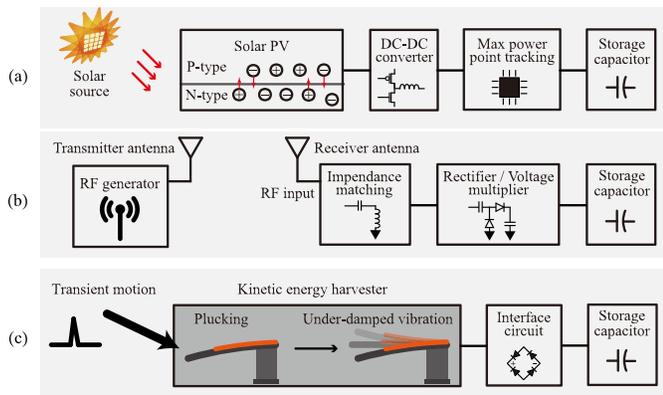


Fig. 1. Comparison of energy harvesting technologies. (a) Solar energy harvesting based on photovoltaic (PV) effect. (b) Radio-frequency (RF) energy harvesting through electromagnetic transmission. (c) Motion energy harvesting via a plucking mechanism. Energy reliability is guaranteed by properly designing the potential energy precharging process.

low-frequency operation and affluent dynamics, a KEH can be better designed to match the source feature by making some specific mechanical modulations [28]. For example, to harness energy associated with slow motion, frequency up-conversion designs, such as the plucking mechanism, are usually utilized. A plucking KEH buffers energy in the mechanical domain and later carries out electromechanical transduction, as illustrated in Fig. 1(c). The mechanical-to-mechanical energy conversion has a perfect coupling coefficient and rapid conversion speed if inertia is sufficiently small. Therefore, the motion energy can be more determinately extracted, in the form of potential energy, for reliably powering some IoT tasks within the lower bound of harvested energy. Such a feature of the buffer-then-convert KEH designs is unique, compared with the PV and RF cases, as well as their convert-then-buffer KEH counterparts [29]. Since the “energy packet” of every single plucking motion is deterministic, the reliability of IoT operations is reinforced.

The plucking mechanism was extensively studied to broaden the energy harvesting bandwidth, in particular, to improve the electromechanical conversion under low vibration frequency [30], [31]. However, nearly all literature about plucking KEH focused on only mechanical dynamics and continuous plucking motions, where harvested power rather than energy was emphasized; the electrical dynamics is simply taken as a linear resistor; no IoT element was included [32], [33]. On the other hand, in other studies focusing on the motion-powered IoT design, only the simplest linear mechanical harvester was used [34], [35]. The mechanical dynamic effect was even neglected for simplicity in some studies [36]. In a word, few studies have investigated or even discussed the synergy among all essential mechanical, electrical, and cyber parts toward a practical transient-motion-powered IoT application yet.

Given the aforementioned challenge and insufficiency in system-level studies, this article introduces a systematic design of a transient-motion-powered sensing node, which is called ViPSN-pluck in short. ViPSN-pluck has integrated energy harvesting, motion detection, and wireless communication

functions. In particular, the plucking design enables concurrent motion energy harvesting and motion information acquisition. The harvested energy is sufficient to power some specific sensing, computing, and wireless communication functions. Instead of relying on continuous motions, such as walking and running, ViPSN-pluck explores an extreme excitation scenario by making use of a single plucking motion, which is discrete and instantaneous. The plucking KEH can be regarded as a mechanical modulator, where mechanical potential energy is precharged before mechanical-to-electrical energy transduction takes place. The potential energy precharging action guarantees the lower bound of harvested energy from a transient motion, such that the IoT tasks, including motion pattern identification and wireless communication, can be reliably executed.

There are three major highlights for this ViPSN-pluck design, which are listed as follows.

- 1) ViPSN-pluck presents a pioneering design toward robust transient-motion-powered IoT applications.
- 2) By emphasizing the potential energy precharging process, ViPSN-pluck raises the attention toward energy-oriented KEH-IoT designs.
- 3) By properly correlating the motion energy generation and motion direction detection and making a cyber-electromechanical co-design, ViPSN-pluck introduces a novel battery-free sensing architecture for motion detection.

II. RELATED WORK

A. Motion Detection

The existing human motion detection is realized through either device-based or device-free solutions. Their features and principles are briefly reviewed and summarized as follows.

Device-Based: Conventional human motion detection requires the users to wear inertia measurement units (IMUs), including accelerometers and gyroscopes [37], [38]. The IMU can provide accurate measurements of motion data. However, the installation and frequent battery recharging are inconvenient and troublesome [39]. Recently, much effort has been devoted to developing battery-free wearable motion detectors. CapBand [15] was designed to recognize human hand gestures by sensing small skin movement of the human wrist via a successive capacitance measurement technique. The system is powered by a solar energy harvesting module. On the other hand, there are some designs powered by the RF energy harvesting technique. For example, a stretchable and flexible skin-interfaced sensing system introduced in [40] was used to record continuous and clinical vital physiological parameters. Its sweat sensor generates electrical signals that are proportional to the concentration of target analytes. It operates like a biofuel cell [41]. In addition, thermoelectric conversion has also been applied to produce electricity from body temperature gradient for powering wearable devices, such as a wristwatch [42], a forehead headphone [43], and other medical sensors [44], [45].

Device-Free: To get rid of the wearable burden, noncontact sensors, including cameras [46], passive infrared sensors,[10],

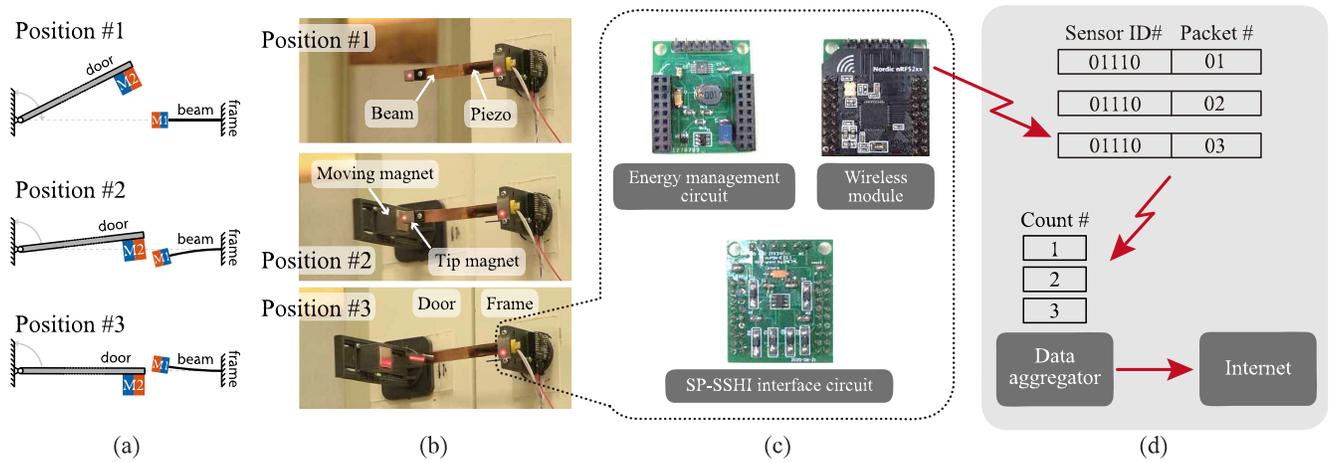


Fig. 2. ViPSN-pluck architecture. (a) Top view of the plucking KEH in three positions. (b) Field installation. (c) ViPSN modules. (d) Data aggregator.

audio-based sonar systems [12], or RF identification platforms [7], [47] were used for building device-free motion detection system. However, these systems have some drawbacks, such as limited information and restricted sensing area, due to ambient noise, weak echo signals, multipath effects, etc. Moreover, the maintenance of a large number of ubiquitous sensors for supporting an everlasting operation is extremely troublesome.

The maintenance problem might be solved by introducing energy harvesting-based battery-free solutions. For example, WISPCam [18], [19], which is remotely powered by an RFID reader, could realize reliable image capture for motion recording and surveillance. The passive RFID tag itself can also be used for motion detection and human tracking. An intrusion detection system, named Twins, was developed based on this principle by leveraging the interference among two passive tags for movement detection [1]. OptoSense [16] is a self-powered sensing system that can infer user activities and interactions according to ambient light intensity. In OptoSense, the ambient light not only generates sensing signals but also supplies energy to support the IoT operations.

B. Kinetic Energy Harvesting

Energy harvesting from human or machine motions is one of the most promising sustainable energy solutions for massively deployed IoT devices [48]. The daily energy consumption of a normal human being is about 1.07×10^7 J, which indicates that the average power is 124 W [49]. Most of the energy is wasted in body motions [50]. Different efforts have been made to extract energy from human motions, such as joint rotation, foot strike, or limb swing and convert the extracted energy into useful electricity [51]. However, human motions are generally in the low-frequency range, i.e., about 0.2–10 Hz. On the other hand, electromechanical transducers generate more power around their resonant frequencies, whose range is around 60–180 Hz. Therefore, to match the preferred frequency ranges of the source and energy harvester, mechanical modulation designs are often needed [28]. The extensively studied mechanical modulation methods for harnessing energy

associated with the low-frequency movement are referred to as the frequency up-conversion mechanisms.

Frequency Up-Conversion: Given the large potential demand for self-powered wearable electronics, various frequency upconversion designs have attracted much research interest in recent years [52]. According to the literature, the existing frequency upconversion methods can be summarized and classified into three major categories: 1) impact-based; 2) snap-through; and 3) plucking designs. Among these solutions, the plucking approach has been used to design many energy harvesters that harness different human motions, such as limb movement [53], [54] and knee-joint rotation [55]–[57]. As illustrated in Fig. 1(c), a plucking motion refers to an action that pushes/pulls a harvester structure away from its elastic equilibrium and then quickly releases it after a certain critical point. The critical releasing point defines the precharged energy in the form of mechanical potential energy. After release, the structure starts an underdamped vibration at its resonant frequency, which is usually higher than that of the driving motion. In this way, the KEH always transiently operates around its resonance, where the transduction power is maximized. The previous studies of plucking KEH focused on the power generation after the frequency upconversion from a low-frequency vibration to high-frequency transient underdamped vibrations without considering any end applications [32], [58]–[60].

When being fully linked with the information demand, it turns out that only a single plucking motion can reliably fulfill fundamental IoT detection and connection. Since we only consider the application of a single plucking motion, the harvested energy, rather than power, is regarded as the key factor for evaluating the feasibility of the plucking KEH in this study.

III. SYSTEM OVERVIEW

The system architecture of ViPSN-pluck, including its mechanical structure for energy harvesting and motion sensing, circuit modules, and data transmission scheme, is illustrated in Fig. 2.

The main structure is a piezoelectric cantilevered beam, which is fixed at the door frame, and a pair of repelling magnets, which are installed at the beam's free end (M1) and the moving door (M2), respectively, as shown in Fig. 2(a) and (b). The three representative positions during the open-door and close-door motions are denoted as positions #1–#3, respectively. In the close-door motion, the door magnet moves through position #1 to position #2 successively and stops at position #3; while in the open-door motion, the door magnet starts from position #3 and moves through position #2 and #1, successively. In either the open-door or close-door motions, the door magnet induces a magnetic plucking action to the piezoelectric cantilever, such that to trigger its transient underdamped vibrations. Energy is harvested in the meanwhile of underdamped vibration.

In order to tell the open-door and close-door motions, the two plucking motions are intentionally designed to be asymmetric by introducing a horizontal misalignment between the center of door magnet M2 and the equilibrium position of beam magnet M1 when the door is closed. Therefore, the amounts of accumulated energy after the two motions are different. Since the harvested energy is approximately proportional to the transmitted packets, the direction information can be obtained by the receiver by simply counting the packet number. The working principle and dynamics of the plucking KEH are discussed in detail in Section IV.

After the plucking KEH, the harvested energy is conditioned in the electrical domain. The development platform ViPSN has provided a well-rounded solution for energy enhancement, energy management, and fundamental IoT applications [61]. The three ViPSN modules used in this design are shown in Fig. 2(c). A self-powered synchronized switch harvesting on inductor (SP-SSHI) power-boosting interface circuit is used in ViPSN-pluck for enhancing the energy harvesting capability [62]. The energy management circuit carries out voltage regulation with the awareness of the energy storage level. The wireless module sends out Bluetooth low-energy (BLE) signals whenever a sufficient amount of energy is collected.

The data aggregator, whose scheme is illustrated in Fig. 2(d), listens for packets from one or multiple ViPSN-pluck motion detectors. Upon packet reception, it counts the number of received packets to identify the motion direction accordingly. Moreover, the data aggregator could also archive the data for historical analysis or send them to the cloud for further analysis, processing, and visualization. In this design, the standard BLE beacon protocol is utilized to broadcast the motion detection information. Thus, any Bluetooth device, such as a smartphone and laptop computer, can work as a data aggregator.

IV. PLUCKING KEH PRINCIPLE

The transient plucking KEH plays an essential role in guaranteeing the performance of ViPSN-pluck. From the energy supply point of view, the transient-motion harvester should harvest sufficient energy during a single plucking motion for supporting the operation of ViPSN-pluck. To enhance the robustness of sensing, computing, and communication and

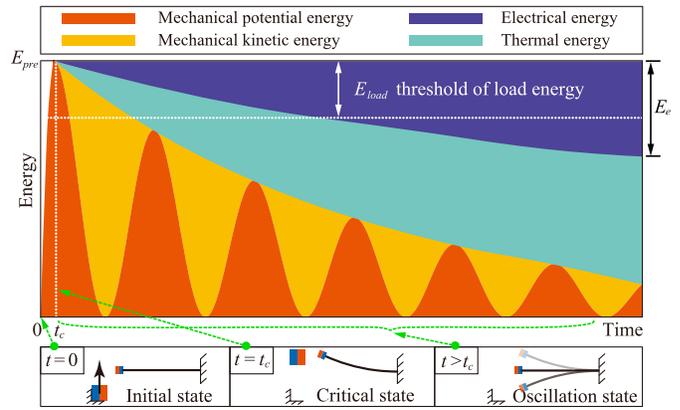


Fig. 3. Energy flow dynamics of an energy harvester under a plucking excitation.

the success rate of direction identification, the mechanical structure must be carefully designed.

A. Transient-Motion Harvester

One of the transient-motion-powered motion detectors is installed at the front door of our laboratory. A piezoelectric cantilevered beam with a tip magnet M1 is installed at the stationary door frame, while the driving magnet M2 is installed at the moving door. During the transient open-door or close-door movements, the driving magnet M2 skims the vicinity of the tip magnet M1. The magnetic force pushes M1 away from its equilibrium. After the tip magnet M1 is brought to a critical position, where the magnetic force could not balance the restoring force of the bending beam, the piezoelectric cantilevered beam is rapidly released. After being released, the cantilevered beam starts to oscillate until the vibration is damped out. In general, a plucking action can be divided into two phases before and after the critical point, i.e., mechanical potential energy precharging and decaying underdamped-free vibration. Instead of expecting a continuous power supply from the harvester, we are interested in how much energy can be harvested from a transient motion, because the harvested energy in a transient determines the run-time behavior of ViPSN-pluck, such as when to execute tasks, when to switch to low-power mode, and when to start communication.

B. Potential Energy Precharging

Fig. 3 shows the energy flow dynamics under a single plucking excitation. There are four forms of energy involved in this process: 1) mechanical potential energy; 2) mechanical kinetic energy; 3) thermal energy; and 4) electrical potential energy. The energy transformations during this process can be summarized as follows.

1) *Plucking Start*: At the beginning, the energy harvester is at its equilibrium position. We set this position the zero-energy position.

2) *Energy Accumulation*: As the driving magnet forces the cantilevered beam to deform, it does positive work to the cantilevered beam. Assuming a very slow plucking motion, in which the kinetic energy can be neglected, the input energy

is collected by the deformed cantilevered beam in the form of strain energy, i.e., the mechanical potential energy of a deformed structure. The potential energy reaches its maximum when the cantilevered beam arrives at the critical position. The total mechanical potential energy at M1 position w and M2 position b can be expressed as follows:

$$U(w, b) = \frac{1}{2}Kw^2 + \int F_m \cos \theta d(b - w) \quad (1)$$

where K is the equivalent stiffness of the beam; w is its tip deflection; b is the position of the driving magnet M2, F_m is the magnetic force, θ is the angle between the repelling magnetic force F_m and movement direction w . The beam deforms until it arrives at the critical position b_c (the very instant is denoted as t_c), where the magnetic force is no longer sufficiently large to counteract the elastic force. At this critical position, the potential energy stored in the cantilevered beam reaches a maximum, as shown by the t_c instant in Fig. 3. The work done by the moving magnet is converted into the potential energy, which is stored in the deformed beam. Therefore, this process is called *potential energy precharging*. The precharged potential energy is a function of the two displacements of M1 and M2 at the critical instant, i.e.,

$$E_{\text{pre}} = U[w_c = w(t_c), b_c = b(t_c)]. \quad (2)$$

3) *Underdamped Vibration*: After passing through the critical point, the cantilevered beam is released from the magnetic lock. It tends to return to its equilibrium position. Since the beam is an underdamped vibrator, it starts a decaying vibration around its equilibrium position under its resonant frequency, as shown in Fig. 3. During the free vibration, the precharged potential energy (E_{pre}) (illustrated in red) is first converted into the mechanical kinetic energy (in orange), then back into potential energy, and back and forth repeatedly. In the meantime, due to the presence of mechanical damping, a part of the energy is dissipated, i.e., converted into thermal energy (in cyan). On the other hand, because of the piezoelectric transducer, a part of the energy is converted into electrical energy and stored in the electrical storage devices, a small capacitor in this study. Since the driving magnet only does work in the precharging phase, the precharged potential energy E_{pre} determines the level of total energy income in a single plucking motion.

In practice, given that the door speed is larger than the quasi-static case, the input energy is actually larger than that in the aforementioned slow motion case. In particular, with the increase of the door speed, the initial kinetic energy increases. Hence, the lower bound of precharged energy is guaranteed. Later experiment shows that, at normal door speeds, the initial kinetic energy is usually much smaller than the initial potential energy. The lower bound of precharged energy can be adjusted by tuning the mechanical structure features, such as the beam geometries (related to elastic potential) and the horizontal gap between magnets M1 and M2 (related to magnetic potential).

A parameter η is introduced to denote the electromechanical energy conversion efficiency, which is related to the mechanical structure, interface circuit, and energy management unit. The harvested electrical energy, therefore, can be simply taken

as part of the precharged energy $E_e = \eta E_{\text{pre}}$. Only when the harvested energy E_e exceeds the kicking-off threshold of ViPSN-pluck, which is denoted as E_{load} , the sensing and wireless communication functions can be fulfilled successfully. Given that the energy consumption of some specific software operations, such as initialization, sensing, and transmitting, is normally fixed, the energy reliability of ViPSN-pluck can be reinforced by carefully measuring the energy demand of the specific IoT functions, designing the mechanical structure, and further making sure $\eta E_{\text{pre}} > E_{\text{load}}$. Such a prechargeable feature before energy transduction is unique in mechanical or motion energy harvesters, compared to their PV and RF counterparts.

C. Potential Energy Pictures

The working principle of the plucking energy harvester and its motion detection function can be better elaborated by looking into its potential energy pictures. Figs. 4 and 5 show the varying potential wells in either open-door or close-door motions, respectively. The potential energy profile progressively changes along with the driving magnet movement. Each plucking motion drives the single-well monostable system to a bistable system, then to another monostable system. Yet, the starting and stopping potential wells are different.

The pictures of the open-door case are shown in Fig. 4. In the beginning, as shown in Fig. 4(a), the cantilevered beam stays still. Due to the presence of the driving magnet M2, whose resting position has a small offset to the right of the beam equilibrium, the cantilevered beam is slightly bent to the left-hand side. From the potential energy profile shown in Fig. 4(f), the magneto-elastic system is a monostable system since there is only one potential well-1. When the driving magnet moves to the left, the cantilever is further bent. A second shallower potential well-2 emerges, as shown in Fig. 4(g). The magneto-elastic system transits from a monostable system to a bistable one. In the following phases, the potential profile evolves from asymmetric [see Fig. 4(g)] to symmetric [see Fig. 4(h)], then to another asymmetric [see Fig. 4(i)] states. Finally, when the driving magnet moves far away from the cantilever harvester, the effect of the driving magnet is negligible. Therefore, the potential profile becomes a linearly symmetric case. The cantilevered beam undergoes a linear underdamped vibration, as shown in Fig. 4(j).

For the close-door case, the evolving pictures are illustrated in Fig. 5. Compared to the open-door case shown in Fig. 4, the process of the close-door motion is reversed. It starts from a linear state and ends at a nonlinear monostable state. The potential pictures from Fig. 4(g)–(i) and Fig. 5(g)–(i) are symmetric. The only difference to distinguish the plucking directions is from the depths of their corresponding final potential wells. The deeper the final potential well, the more energy is generated. As the moving magnet stops at negative infinity in the open-door case and the rest position b_r in the close-door case, respectively, an asymmetrical design is realized. Since the final well of the transient-motion harvester in the close-door process is shallower, the harvested energy in the close-door process is less. According to this feature, the

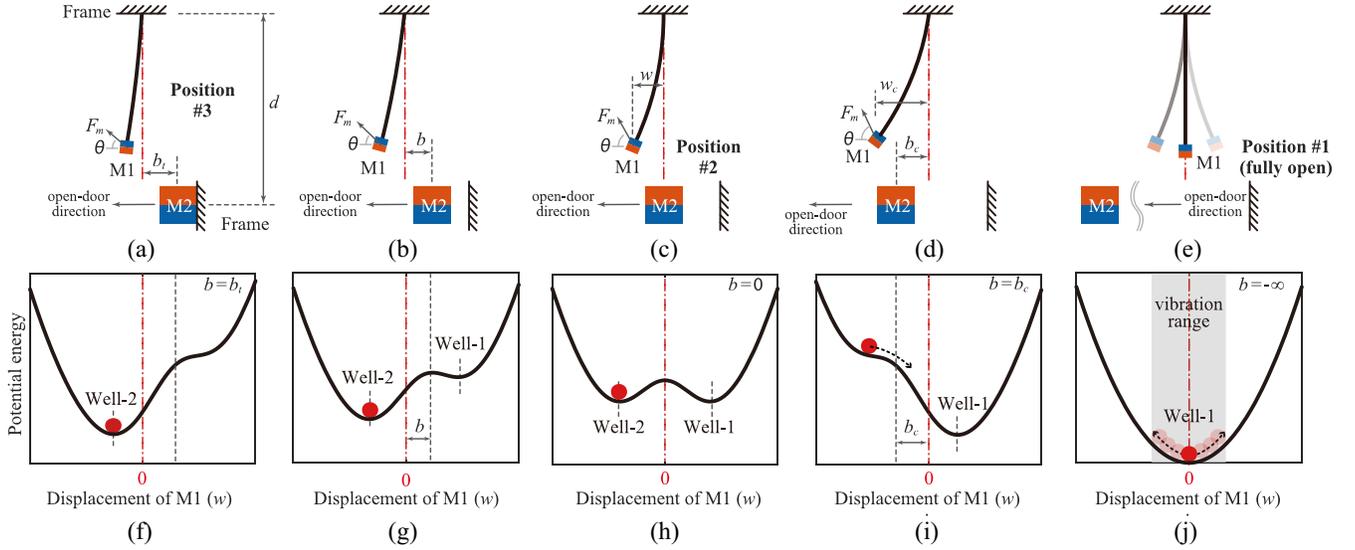


Fig. 4. Plucking dynamics in the open-door movement. (a)–(e) Beam positions. (f)–(j) Potential energy pictures. (a) and (f) Starting position #1 with a monostable potential well. (b) and (g) Intermediate position with two asymmetric wells. (c) and (h) Intermediate position #2 with two symmetric wells. (d) and (i) Critical position at which the energy barrier disappears. (e) and (j) Final position #3 ending up with the beam vibration in a single linear well.

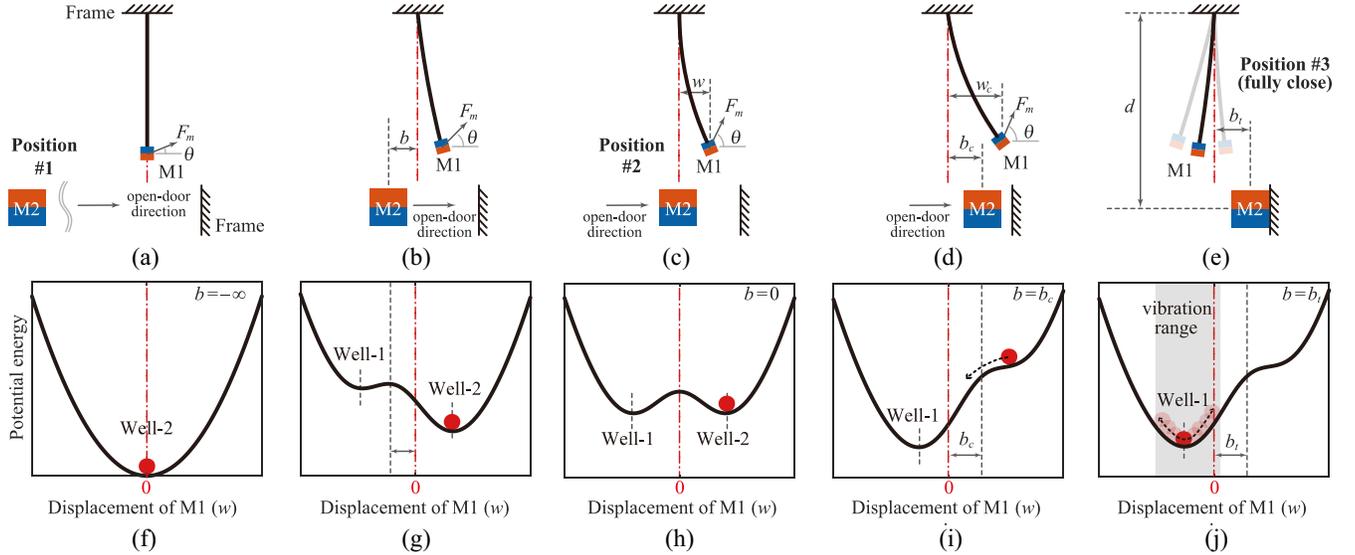


Fig. 5. Plucking dynamics in the close-door movement. (a)–(e) Beam positions. (f)–(j) Potential energy pictures. (a) and (f) Starting position #3 with a single linear potential well. (b) and (g) Intermediate position with two asymmetric wells. (c) and (h) Intermediate position #2 with two symmetric wells. (d) and (i) Critical position at which the energy barrier disappears. (e) and (j) Final position #1 ending up with the beam vibration in a monostable nonlinear well.

motion direction can be differentiated based on how much energy is captured during a single plucking excitation.

The potential energy picture of any bistable or monostable system can be described with a third-order polynomial as follows [63], [64]:

$$U(w) = \frac{1}{2}(K - \alpha)w^2 + \frac{1}{3}\beta w^3 + \frac{1}{4}\gamma w^4 \quad (3)$$

where α , β , and γ are the polynomial coefficients to approximate the magnetic potential. They represent the additional linear, quadratic nonlinear, and cubic nonlinear stiffnesses, respectively, which are brought in by the magnet pair. Once the magnetic strengths of the magnets are provided, these three

parameters are related to the distance b , the position of the driving magnet M2.

As shown in Fig. 4(c) and (h) and Fig. 5(c) and (h), when the driving magnet M2 arrives at position #2, we have $\beta = 0$. At this position, we obtain a symmetric double-well bistable potential profile. As the driving magnet slightly moves away from position #2 to either direction, β becomes positive (close-door) or negative (open-door). The two potential wells become asymmetric. The potential barrier is separating the two wells decreases as β getting more positive or negative. For example, in the open-door motion, as the left well-1 gets elevated and the right well-2 gets deepened gradually, the left well-1 will eventually disappear, as shown in Fig. 4(i). After passing through the critical position, only the

TABLE I
ViPSN-PLUCK SPECIFICATIONS

Module	Specification		
Energy harvester	Transducer	Size	$8 \times 50 \text{ mm}^2$
		Material	PZT
	Beam	Size	$100 \times 10 \times 0.53 \text{ mm}^3$
		Material	Copper sheet
	Magnet	M1	$10 \times 10 \times 10 \text{ mm}^3$
		M2	$20 \times 20 \times 20 \text{ mm}^3$
Deployment Configuration	d	150 mm	
	b_t	30 mm	
Interface circuit	Parallel-SP-SSHI [65]		
Energy management circuit	DC-DC	LTC3588-1 [66]	
	Comparator	MIC841 [67]	
	Storage	10 μF capacitor	
Wireless module	Hardware	nRF52832 [68]	
	Software	BLE beacon	

TABLE II
ENERGY STATISTICS

Operation	Energy (μJ)	Duration (ms)
micro-controller initialization	72.70	53.8
Radio initialization	68.47	13
Beacon broadcasting	60.37	5

right well-2 lefts. The cantilevered beam is trapped in well-2 and vibrates, as shown in Fig. 4(j). The mathematical model helps describe the evolution of potential wells in either motion direction.

V. IMPLEMENTATION AND EVALUATION

A. Hardware Platform

The prototype of ViPSN-pluck is shown in Figs. 2 and 8. A piezoelectric cantilever is used as the kinetic transducer. The holding fixture of the transient-motion energy harvester is manufactured using a 3-D printer. The other three circuit units are developed based on ViPSN [61], an opensource development platform for vibration-powered IoT devices.¹ The specifications of ViPSN-pluck are listed in Table I. In the energy management circuit, an LTC3588-1 IC [66] developed by Linear Technology Inc. is adopted for voltage regulation. It integrates a low-loss full-wave bridge rectifier and a high-efficiency buck converter. MIC841 [67], a micropower precision-voltage comparator with adjustable hysteresis, is used to detect the energy level of the storage capacitor. A 10- μF storage capacitor, which satisfies the minimum energy demand for at least two rounds of IoT operations, is selected. A programmable nRF52832 BLE system on chip (SoC) by Nordic Inc. [68] is utilized for sensing and wireless communication. A smartphone is used as a data aggregator. It receives the packets from ViPSN-pluck, processes the data, and handles the Internet connection.

B. Basic Operation

Fig. 6 shows the energy, supply, and load current in a complete operation cycle of ViPSN-pluck when it is activated. After a single plucking excitation, as some potential energy is converted into electricity via the beam energy harvester,

¹<https://github.com/METAL-ShanghaiTech/ViPSN>

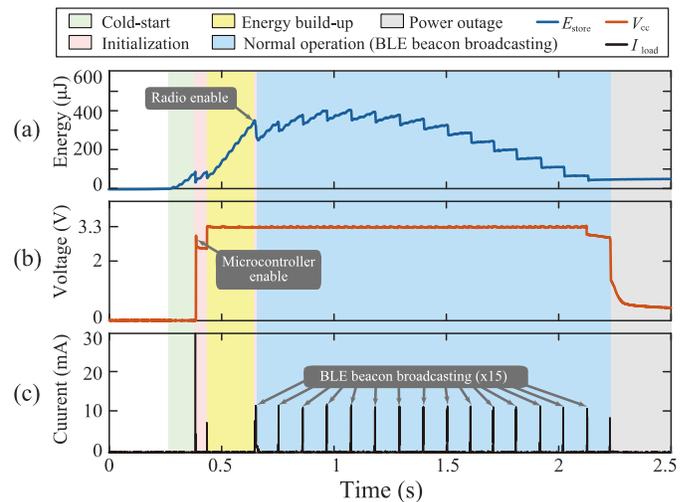


Fig. 6. Workflow of ViPSN-pluck during one plucking motion. (a) Storage energy E_{store} . (b) DC voltage output V_{cc} . (c) Load current.

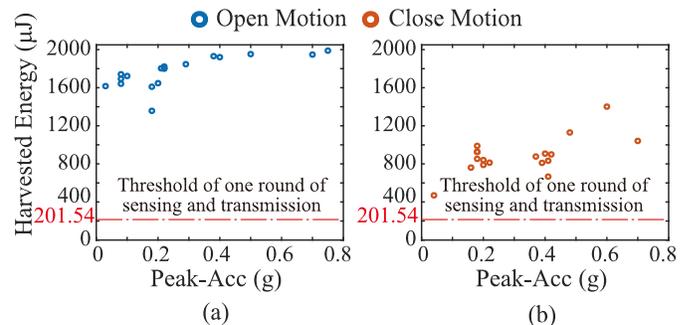


Fig. 7. Measured harvested energy under different door speeds. (a) Open-door motion. (b) Close-door motion.

the storage energy E_{store} increases. When it reaches a specific threshold, the buck converter in LTC3588-1 is activated to provide a regulated 3.3-V voltage supply to boot up the microcontroller, as shown by the steep rising edge in Fig. 6(b). Subsequently, after a brief energy rebuild-up phase (in yellow), robust radio wake-up is robustly achieved without meeting unexpected energy outages. As a result, BLE beacon packets can be sent out later at a constant time interval. As shown in Fig. 6(c), more than 15 BLE beacon packets are sent out after one plucking motion. The number of the BLE beacon packets also implies information about the harvested energy level from this specific plucking action. Finally, at the end of this operation cycle, the microcontroller exits the active mode, and the LTC3588-1 disconnects the voltage supplier. The system enters the deep-sleep mode and waits for the next plucking excitation.

C. Energy Reliability

Fig. 7 shows the energy harvesting performance of the ViPSN-pluck prototype under open-door and close-door excitations. Experiments are carried out under different door accelerations, whose peak values range from 0.03 to 0.6 g. Experimental results demonstrate that during either the open-door or close-door process, ViPSN-pluck can robustly harvest

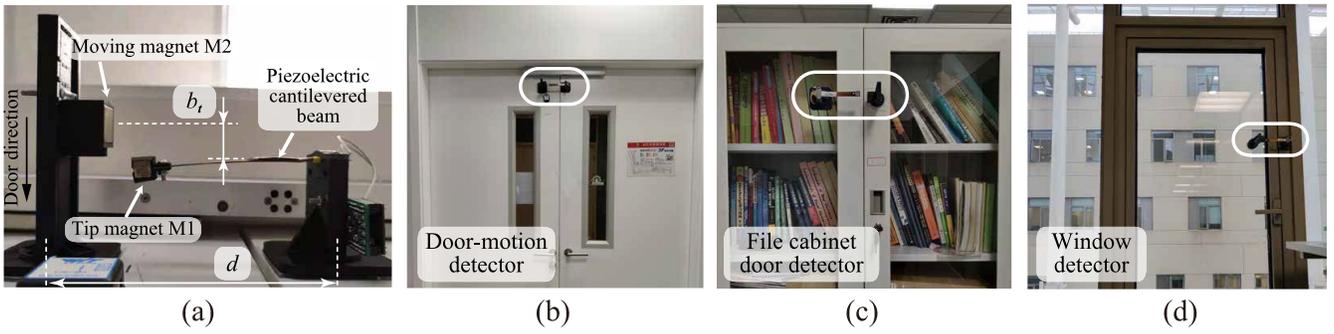


Fig. 8. ViPSN-pluck prototypes in field tests. (a) Deployment configuration. (b) Door motion detector. (c) File cabinet door detector. (d) Window detector.

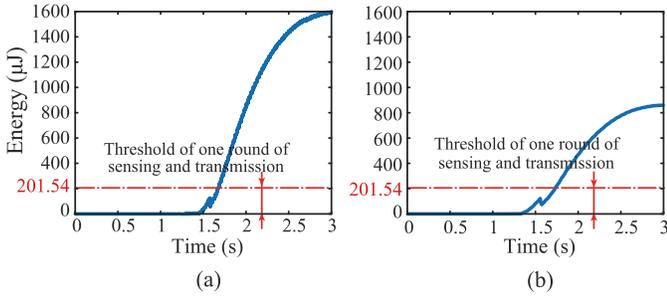


Fig. 9. Charging history. (a) Open-door motion. (b) Close-door motion.

at least 400- μJ electrical energy. Given the nominal energy consumption of a BLE IoT operation, including the three functions listed in Table II, is about 201.54 μJ , the harvested energy from a single open-door or close-door motion can satisfy the energy demand of ViPSN-pluck.

D. Motion Direction Identification

From the experimental results shown in Fig. 9(a) and (b), we can see that, for this ViPSN-pluck prototype, the harvested energy can be accumulated to about 1600 and 850 μJ in open-door and close-door motions, respectively, in around 1 s. Fig. 10(a) shows the measured harvested energy under different rest positions of the driving magnet M2, i.e., b_t parameter. Fig. 10(b) shows the average energy differences under different b_t . As mentioned in Section IV-C, the dynamic behavior of the asymmetric well can be set by tuning b_t . When b_t is larger, the magnetic force produced by M2 and applied to the tip magnet M1 becomes weaker. Therefore, the depth of the final asymmetric well-1 is closer to that of the linear well-2. The harvested energy in the two plucking directions are closer under large b_t . On the other hand, for the plucking motion in either direction, if b_t is too small, i.e., the M2 rest position is closer to the M1 equilibrium, the initial well is too shallow to provide large input energy. It can be observed from the measurement results shown in Fig. 10(a) that less energy is harvested under smaller b_t . Therefore, the energy difference between open-door and close-door processes can be optimized by tuning the rest position of the driving magnet M2. The different harvested energy under different b_t is shown Fig. 10(b). We set b_t to 30 mm in all experiments

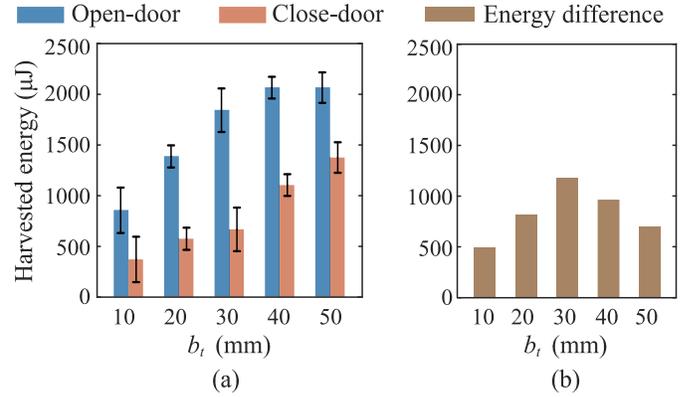


Fig. 10. Harvested energy under different b_t , the rest position of M2. (a) Harvested energy with different motions. (b) Difference in average energy.

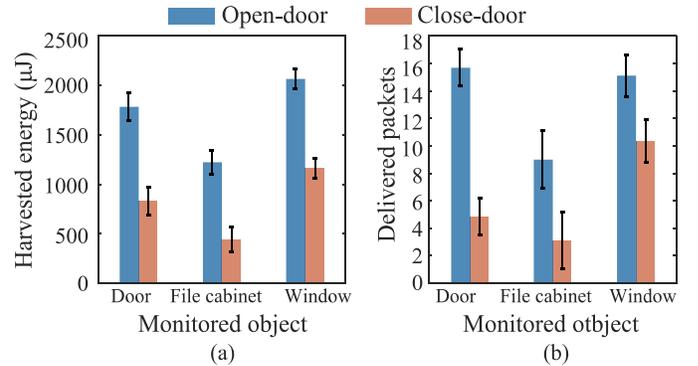


Fig. 11. Performance of ViPSN-pluck in several real-world scenarios. (a) Harvested energy from several object movements. (b) Delivered packets.

since it gives the most significant energy difference for better plucking direction identification.

The software code of ViPSN-pluck is optimized to ensure a rapid and robust response. Each plucking activation consists of one initialization and several radio transmissions. The energy consumption for each operation is rather stable as listed in Table II. Since the energy consumption of a beacon broadcasting is almost the same, about 60.37 μJ , the harvested energy is roughly proportional to the possible sent-out packets. By counting the number of BLE beacon packets received by the data aggregator, as illustrated in Fig. 2(d), the plucking direction can be identified.

E. Field Test

After the experimental test to investigate the performance of ViPSN-pluck under various parameters, a field test is carried out to test the actual feasibility of ViPSN-pluck in real scenarios. Fig. 8 shows the field setup and the ViPSN-pluck prototypes installed in three field applications to detect and identify the open-door/close-door actions. The prototypes are installed at the front door, a file cabinet, and a window in our laboratory, as shown in Fig. 8(b)–(d), respectively. Table I and Fig. 8(a) show the specifications and deployment configuration.

Fig. 11(a) shows the harvested energy in the open-door/close-door motions in different scenarios. Fig. 11 shows the number of the delivered BLE beacon packets, which is recorded and counted by the data aggregator. In this field test, we use a smartphone as the system terminal. In different scenarios, there are some differences due to the influence of environmental conditions. For example, the material of monitored objects would affect the magnetic field of the magnets. As shown in Fig. 11(a), under the same configuration, the energy harvested by ViPSN-pluck deployed in the file cabinet (made of steel) is less than that in the window case (made of aluminum alloy) and that in the front doorcase (made of wood). In addition, there are also some differences due to the plucking kinetic energy fluctuates. But, in general, the experimental results show that the harvested energy is always more than the energy demand for a round of sensing and wireless transmission. At least 500 μJ of electric energy can be harvested to run the IoT functions. At least four beacon packets can be received to identify the motion directions.

Besides those scenarios shown in Fig. 8, ViPSN-pluck, as a self-powered motion detector, can also be deployed in many other applications, such as archives management, furniture safety, warehouse, and logistics. These realizations allow ViPSN-pluck to interconnect many moving things in the real world, either directly or indirectly.

VI. CONCLUSION

This article has presented a transient-motion-powered IoT motion detector, which is called ViPSN-pluck. It is developed based on a cyber-electromechanical synergetic co-design. The development of ViPSN-pluck involves knowledge from multiple disciplines, including mechanical dynamics, electrical power management, and low-power embedded systems. Through the sophisticated collaboration between the mechanical harvester configuration and software codes, the associated motion information can be sent out with an off-the-shelf BLE wireless module.

To address the sustainable power supply issue, a transient-motion harvester has been designed for ViPSN-pluck. Different from the solar or RF energy harvesting solutions, which might be constrained by fluctuating sources, the transient-motion harvester has a unique feature to provide a highly reliable energy supply to self-powered applications. Such a feature benefits from its potential energy precharging mechanism. To realize simultaneous motion detection, a novel motion detection mechanism has been conceived according

to the dynamic characteristics of the transient-motion harvester. By making an asymmetric design, the amounts of harvested energy by the transient-motion harvester from different plucking directions are different. Owing to this feature, motion direction can be identified by counting the sent-out beacon packets, which are roughly proportional to the harvested energy. Therefore, in ViPSN-pluck, the energy harvester itself also acts another important part as the motion detector.

An experimental test has shown that the energy harvested from a single plucking excitation can be up to 2000 μJ , which is far more sufficient to power the basic operation of ViPSN-pluck. A field test in three real-world scenarios has validated the robustness of ViPSN-pluck for motion detection. In general, the work presented in this study provides valuable guidance for the design and development of future motion-powered IoT systems.

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