

VIB3D: Microvibration Harvesters for Context-Aware Sensing using FDM

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Fig. 1. VIB3D is a low-cost FDM-printed, self-powered, miniaturized vibration sensor for capturing everyday interactions and contextual signals, from workout quality and compressor performance to unique material identification and personal hygiene logging.

The physical world quietly encodes human activity and object context through microvibrations produced by everyday interactions, from tapping and rubbing to swinging and striking. While such vibrations have been explored as a sustainable power source for ubiquitous sensing, interaction-driven harvesting remains underutilized due to limited awareness of vibration-based sensing opportunities, fabrication complexity, and uncertainty about whether harvested energy can support practical sensing.

We introduce VIB3D, a design and fabrication approach for harvesting everyday microvibrations as distinct profiles for context-aware sensing. VIB3D combines a scanner and parametric design framework that enables non-experts to customize low-cost FDM-printed harvesters from off-the-shelf materials, based on energy needs, spatial constraints, and target interactions. By tuning batteryless sensing to specific objects and contexts, VIB3D enables everyday objects to become sustainable sensing sites for mobile and ubiquitous computing.

CCS Concepts: • **Human-centered computing** → **Interactive systems and tools**.

Additional Key Words and Phrases: Personal Fabrication, Batteryless Vibration Sensing, AI-Assisted Design.

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1 Introduction

We live with an ever-growing demand for energy due to millions of ubiquitous computers and embedded sensors for daily context-aware activity sensing. Energy harvesting offers a novel solution for this through the concert of electronic devices, sensors, and numerous IoT systems in an environmentally friendly and self-sustaining manner. In addition to traditional natural sources (e.g., wind and solar), researchers are also investigating the potential of small, ambient sources to support the massive inflow of ubiquitous computing devices. The exploration of mechanical vibration, a byproduct of human interaction with physical objects, has received considerable attention as a more sustainable option. From the gentle tapping of a door to the rhythmic hum of an appliance, these vibrations carry rich contextual information about activities, states, and environments [49], such as how frequently a runner had their exercise, whether the HVAC systems are on full capacity to sustain a comfortable indoor environment, monitor foot traffic in smart homes, and many more. Harnessing vibrations can enable systems to passively monitor user behaviors and infer interaction states without intrusive sensors, more importantly, nearly zero impact on sustainability by the kinetic energy extracted itself to self-power those event detection and state monitoring.

Despite such innovative approaches towards sustainable sensing through energy harvesting, there remain two outstanding end-user challenges to widely adopt this findings to daily sensing to innovate personal lives. Often, novices do not know what daily interactions can be sensed by their unique vibration patterns. Furthermore, average users do not have access to easy-fabrication of vibration sensors. As piezoelectric or triboelectric-based vibration energy harvesters can not be fabricated on the go, increasing availability of consumer-grade 3D printers promises easy fabrication of MEMS-based harvesters, built as resonant microstructures, to provide a scalable way to convert everyday object vibrations into electricity. Prior works often rely on specialized machines and exotic materials, such as Selective Laser Sintering (SLS) or Inkjet printing [25], however, this reliance on high-end technology poses a significant accessibility barrier for a broad spectrum of potential users and researchers. Limited access to fabrication tools and methods impedes the wider adoption and exploration of vibration-based energy harvesting technologies, thus hampering their potential to address the growing demand for energy solutions in various applications.

We present VIB3D, a unique user workflow of identifying potential vibration sources, turning them into sensible activities, and fabricating custom adjustable harvester modules tailored for capturing unique vibration profiles to fine-tune sensor configurations using FDM. By utilizing energy generated from interactions as an indicator of interaction patterns, VIB3D serves as both a self-powered sensor and an energy harvester. We investigate the conception and construction of the harvester design parameters, intended to empower individuals without access to costly, specialized equipment or materials, thereby democratizing the process and drawing on human interaction sensing principles to induce rich contextual information from daily objects and activities.

2 Related Works**2.1 Batteryless Computing Devices**

Beyond conventional sources such as wind and solar, ambient light [3, 50] and mechanical energy from roads, rail tracks, shoes [56], and indoor environments can be harvested using piezoelectric, electromagnetic, or triboelectric transducers for interactive systems [51]. Prior work has explored

generators, transformers, turbines, inductors, and MEMS for mechanical energy harvesting [7]. Batteryless devices build on intermittent computing [20], where systems operate only when sufficient energy is available, as seen in Peppermill [46] and the battery-free Game Boy [12]. These approaches enable ultra-low-power operation and long-term deployment without battery replacement, particularly in mobile and on-the-go contexts where continuous power is unavailable. Techniques include reducing computation overhead [32], runtime adaptation [21], and user-driven energy generation [4, 12]. Built on electromagnetic induction, VIB3D provides a practical alternative to piezoelectric and triboelectric methods, offering improved power delivery, scalability, and adaptability through simple construction and widely available 3D-printable materials. It supports intermittent computing by harvesting energy just-in-time for interaction-driven sensing.

2.2 Sensing Vibration as a Signal

As daily human activities generate energy across scales, from walking and running [22, 31, 45] to interactions with textiles [41] or paper [55], they produce vibration patterns detectable at micro-scale (swipe, touch, speech [5], writing, sitting, typing [8, 29, 36], single-handed gestures [26]), meso-scale (vacuuming, walking, kettle use [33], floor-based occupant activity [54], appliance usage [38]), and macro-scale (transportation [47], wireless acceleration sensing [18]). Vibrations provide rich signals enabling reduced power consumption [39] and diverse sensing of voltage [16], from suspension [23], direction [13, 48], friction intensity [10], biomechanical motion [14], air-flow [27], and occupancy and power use [9]. Such signals support mobile computing and smart sensing [17] through Triboelectric nano-generators (TENGs) for self-sustained devices [6, 28, 30], radio tags [53], and photodiodes or thermoelectrics [5]. While optimization across frequency ranges, degrees of freedom, and hybrid conversion can improve efficiency [24], piezoelectric and TENG devices require consistent high-frequency stress or friction, limiting reliability; electromagnetic harvesters (e.g., [52]), by contrast, are tunable and versatile for diverse vibration patterns, making them a more promising foundation for VIB3D.

2.3 3D Printed Energy Harvesters

Advances in machines and materials have made 3D printing a cost-efficient, flexible, and sustainable approach to fabricate self-powered sensing devices [44] and energy harvesters [1, 25, 35]. These harvesters capture energy from daily interactions such as spring-based motion [19], button presses [12], embodied VR actions [40], or 3D-printed attachments on moving objects [4, 49]. Beyond electromagnetic designs [15], integration with piezoelectric and triboelectric mechanisms shows promise for sustainable and autonomous systems [11, 34, 35, 43]. Yet, practical use is limited: piezoelectrics need precise crystalline structures, triboelectrics depend on specialized material pairs, and MEMS-based approaches [25] require expensive printers. Low-cost alternatives such as DC generators are often bulky, require rotational motion, and lack adaptability to diverse, irregular vibrations common in mobile and everyday contexts [4, 49]. These limitations—design complexity, fabrication barriers, and lack of adaptability—restrict broader adoption in mobile and ubiquitous computing scenarios where lightweight, deployable, and interaction-driven sensing is critical. VIB3D addresses this gap by enabling end-users to design and fabricate adaptable vibration energy harvesters using standard 3D printers, supporting batteryless sensing across everyday contexts. We position our work in Figure 2.

	Energy Harvesting	Battery-less Sensing	State Sensing	Activity Sensing	Scalability of Mechanisms	Support for End-User Fabrication	Adaptability with Everyday Objects	Cost-effective	Availability
Piezoelectric [22], [31], [45]	✓	✓	✓	✓	✓			✓	✓
Triboelectric [30], [34], [43]	✓	✓	✓	✓					
Geophone [33], [54]	✓	✓	✓	✓			✓		✓
MEMS [25]	✓	✓	✓	✓	✓		✓		
IMU [36]			✓	✓			✓		✓
VIB3D	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ Possible within limited scope

✓ Possible with broader scope

Fig. 2. Situating VIB3D.

3 Vibration Energy Harvester Design

3.1 Point of Departure: Off-the-Shelf Piezoelectric Sensors

In ubicomp research, piezoelectric harvesters are the most accessible off-the-shelf option, while electromagnetic and electrostatic devices remain largely prototypes. They generate energy by converting mechanical strain (bending, flexing, or impact) into charge. We evaluated commercially available 27 mm piezo disks (\$0.46/ea) by attaching them to 10 everyday objects—doors, drawers, bins, cabinet, refrigerator, faucet, and switch—and three surfaces (wood, glass, metal). Each was actuated through typical interactions (e.g., opening a door) or tapping, and the resulting voltage waveforms were recorded with an oscilloscope under a 10kΩ load [37] (Figure 3a).

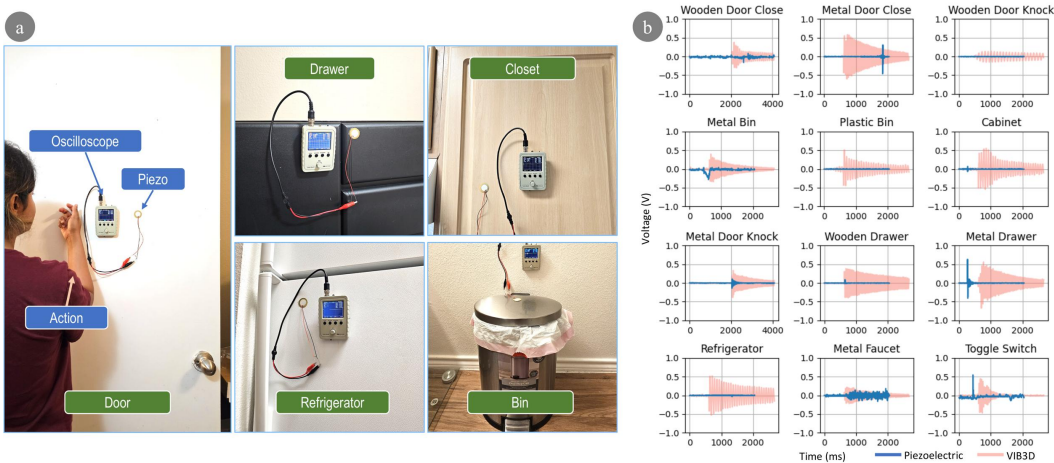


Fig. 3. (a) Testing piezoelectric disks attached to everyday objects with output measured using an oscilloscope. (b) Voltage Waveform of the Piezoelectric Disk attached to different objects.

We found piezo devices produced measurable energy mainly on metal objects (e.g., drawers, faucets) and under high-impact forces (e.g., falling objects, door slams). Metals generated sinusoidal waveforms, while impacts yielded brief microsecond spikes (Figure 3b). Most everyday interactions (e.g., refrigerator doors) produced negligible output. Two limitations emerged: a mismatch between object vibrations and the disks’ high resonant frequencies (kHz range), especially for low-frequency materials like wood; and impacts producing only short broadband deformations. Direct tapping on the piezo gave higher energy, suggesting a need for tunable materials or adaptive resonance to capture diverse interaction signatures.

3.2 Electromagnetic Vibration Energy Harvesting

Interactions with everyday objects generate vibrations that propagate through their rigid bodies. In a electromagnetic harvester design, a magnet suspended by a spring converts this mechanical energy into oscillatory motion. The magnet resonates at a frequency determined by the spring constant k and its mass m , expressed as $\omega = \sqrt{\frac{k}{m}}$. By adjusting k , the harvester can be tuned to align with the dominant frequency of the source vibration. As the magnet oscillates relative to a surrounding coil, it induces an electromotive force (EMF) according to Faraday's law of electromagnetic induction (Figure 4), thereby transforming interaction-driven vibrations into electrical energy.

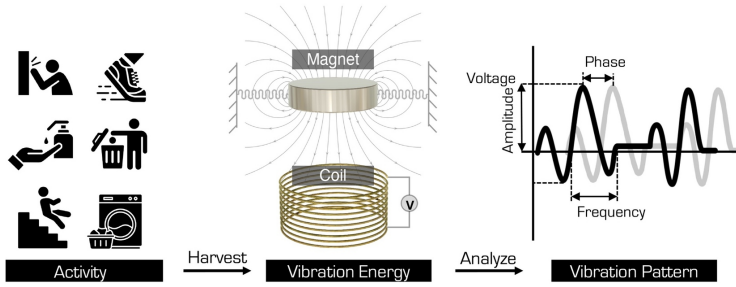


Fig. 4. Different activities and appliances generate distinct vibration patterns (e.g., frequency, duration, and phase), whose energy can be harvested and identified through electromagnetic induction.

Prior work showed 3D-printed electromagnetic harvesters using flat springs fabricated via inkjet printing [25], but the approach depends on specialized equipment. We attempted to replicate the design (Figure 5a), yet found no available inkjet services; even selective laser sintering (SLS) through professional services remained costly, inaccessible, and prone to tolerance issues and line breakage.

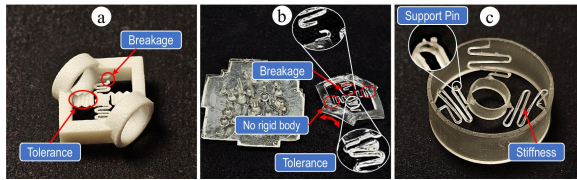


Fig. 5. Failure investigation of vibration energy harvesters [25] fabricated by (a) SLS & (b) SLA 3D printing, and (c) a modified design fabricated using SLA 3D printing, showing breakage, tolerance, and rigidity issues.

These limitations raised two questions: (1) how to fabricate electromagnetic harvesters by 3D printing, and (2) how to parameterize designs for everyday contexts. We reconstructed the spring-based harvester from prior work and printed it using SLS printing (via professional service, Shapeways), but tolerance issues caused breakage or fused springs. Reprinting with SLA (Egloo Mars3) offered higher resolution but springs still broke during support removal or lacked stiffness to hold magnets (Figure 5b-c). Thickening the springs reduced vibrations, rendering them ineffective. While being cheap and accessible is the most comparable benefit of FDM, there are increasingly wider material options available; we chose the FDM to optimize geometries for the best electromagnetic vibration harvesting performance and possibilities for fine-tuning, drawing on Hooke's law, as follow.

4 Optimization of Harvester Geometries for FDM 3D Printing

Informed by the principle of energy conversion affecting the harvester's performance, in this section, we detail the parametric design of a miniaturized harvester with a cantilever beam as the simplest spring primitive for the vibration energy harvester (Figure 6a). When an external force is applied, the beam bends which follows Hooke's law, with bending stress proportional to strain. The effective spring constant, which determines the resonating frequency, depends on the material's Young's modulus, the second moment of area, and beam length.

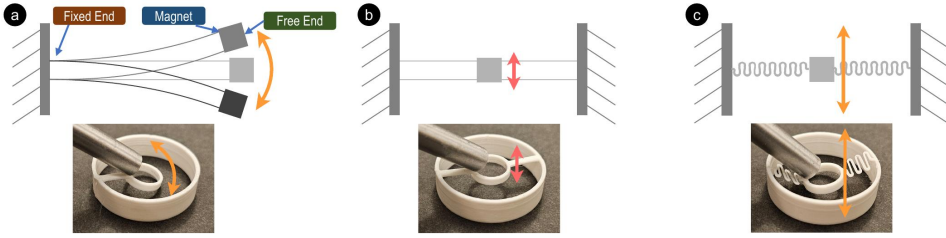


Fig. 6. Front view of (a) Cantilever oscillation, (b) allowing the magnet to oscillate linearly with two cantilevers, and (c) utilizing springs as cantilevers for oscillation.

For disk or cylindrical magnets, magnetic flux lines align perpendicular to the surface, requiring linear motion along the coil axis. Suspending the magnet with two cantilevers to achieve this motion limits oscillation amplitude (Figure 6b) due to restricted stretchability. To address this, we replace the rectangular cantilever with a flat spring design that allows greater deformation and higher oscillation amplitude while preserving linear motion (Figure 6c). The spring constant can be tuned by adjusting geometric parameters such as cross-sectional area, width, length, and number of loops to match the target resonance. A vibration energy harvester can be tuned through such design and fabrication parameters. A VIB3D module consists of four main components—(i) flat spring, (ii) shell, (iii) magnet holder, and (iv) coil holder (Figure 7a)—and its energy output is closely tied to resonant frequency and oscillation amplitude. We begin by defining spring primitives and then extend to the full harvester design.

4.1 Spring Primitive

The spring has several design parameters (Figure 7b) that affect energy harvestability and printability. These parameters contribute to the stiffness or spring constant of the harvester and hence enable the harvester to resonate at a target frequency to provide maximum throughput.

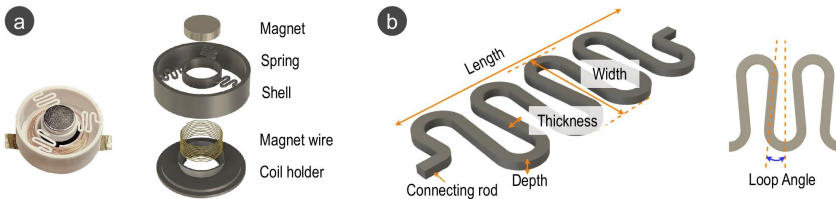


Fig. 7. (a) Construction of a VIB3D module, and (b) Spring Design Parameters.

Spring Length: The length of the spring depends on the dimensions of the module and magnet, specifically constrained by their radii. Small rods attached to each end of the spring connect it to

the shell and magnet. If the shell radius is R_s and the magnet radius is r_m , the spring length (L_s) is given by: $L_s = R_s - r_m - 2 * l_{rod}$, where l_{rod} is the rod length. This formula accounts for the space taken by the magnet and rods, ensuring proper spring alignment within the assembly.

Spring Width: The width of the spring can be adjusted, but is limited by the maximum width allowed by the shell's radius. A smaller radius reduces the available space at the spring's end, decreasing the clearance between the spring and the inner surface of the shell, as described in Section 4.2. Spring stiffness is inversely proportional to the spring width.

Depth: The spring's depth (z-height) controls stiffness and load-bearing capacity: increasing depth improves strength but reduces flexibility and sensitivity, while decreasing depth enhances responsiveness but may not support the magnet's weight. Hence, the spring stiffness is proportional to the depth. The minimum depth is constrained by printing limits (typically 0.1–0.2 mm). Our tests on cantilever structures show that at least 3 layers and a 0.3 mm depth are required for reliable printing and durability (Figure 8a).

Thickness: Similar to depth, spring thickness contributes to stiffness. A wider spring is stiffer but less flexible, while a narrower spring is more responsive but less durable under repeated vibration. The minimum thickness is constrained by the printer nozzle width, typically 0.4 mm.

Loop Angle: The loop angle contributes to stress distribution. Our tests showed that adding a loop angle significantly enhanced durability, reducing spring breakage compared to parallel designs (0° loop angle). Loop angle also contributes to the first layer adhesion as the nozzle moves along a longer arc. Given the spring length (L_s), number of loops (n_l), and width (W_s), the maximum loop angle is defined as $\theta_l = \arctan(L_s/4W_sn_l)$. However, in practice, the loop angle must be smaller than this to prevent layer overlap during 3D printing due to nozzle limitations.

Number of Loops: The number of loops in a flat spring also influences its mechanical properties and performance. Each additional loop increases the spring's flexibility, enabling it to undergo larger deflections while maintaining its structural integrity. However, a greater number of loops also tends to decrease the spring's load-bearing capacity per unit of deflection. The number of loops is constrained by the spring length. Placing loops too close to each other can lead to overlap during 3D printing extrusion.

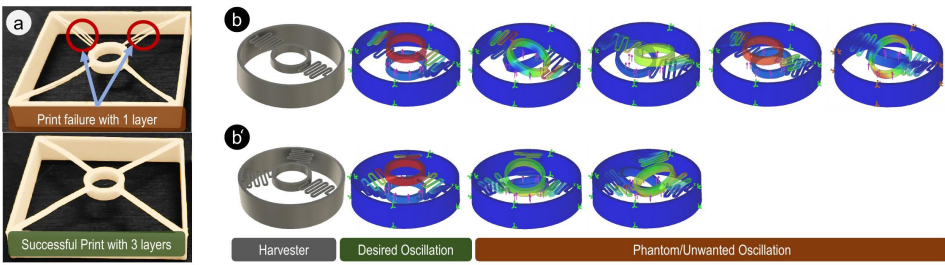


Fig. 8. (a) Minimum printable spring depth. (b-b') Oscillation modes with two and three springs.

Number of Springs: The number of springs controls both the overall spring constant and the degrees of freedom of magnet oscillation. Concatenating n springs, each with spring constant k , the parallel spring combination rule gives a total stiffness $k_n = nk$, with corresponding resonant frequency $\omega_n = \sqrt{\frac{k_n}{m}} = \sqrt{n} \cdot \omega$. To study oscillation behavior, we used SolidWorks simulations with a 0.1N impulsive force (Figure 8b–b'). Vertical oscillations induces clean sinusoidal voltage in the coil, while lateral motions introduce noise and reduce durability. Increasing the number of springs

constrains motion to the vertical axis and raises stiffness and resonance; we found a three-spring design to be optimal for stable oscillation and durability (Section 7).

4.2 Container Shell

Global Shape: We explored various harvester shapes, building on prior high-resolution 3D printing work [25]. Starting with a rectangular design to maximize spring length and width (Figure 9a), we found that shell geometry constrains spring shape. To maximize energy while minimizing size, we evaluated polygonal forms: smaller angles restrict spring width, whereas more vertices with wider angles allow larger widths (Figure 9b). We also observed that close shell–spring proximity can cause overlap during printing. Based on these tradeoffs, we adopt a circular shape, which offers maximum flexibility for tuning the spring design.

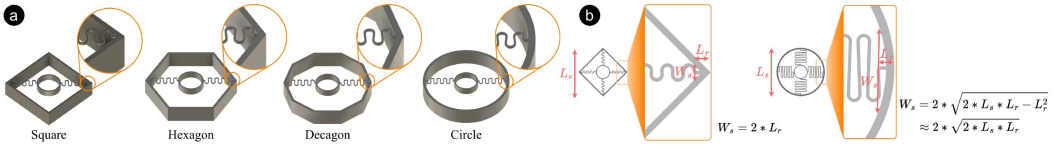


Fig. 9. (a) Different shapes of the harvester: square, hexagon, decagon, and circle. (b) Relationship between size of the shell and width of the spring for square and circular harvester.

Scale: The scale of the mechanism is highly dependent on the size of the magnet. A larger magnet, potentially creating a larger magnetic flux change, occupies a larger area inside the shell, leaving a shorter spring length possible. Another parameter related to the scale of the mechanism is the amplitude of vibration. If the vibration amplitude is high, the spring needs to be longer to correspond to the vibration without any plastic deformation.

Height: Although the magnet can freely ascend without hindrance, too short a gap with the solenoid underneath may impede its vertical movement. To facilitate unrestricted vertical motion, it is necessary to ensure sufficient clearance for the magnet to oscillate freely within the shell. As the radius of the shell expands, it becomes imperative to correspondingly adjust the height of the shell to accommodate the increased range of motion.

Magnet Shape and Holder: The magnet holder is located in the center for the insertion of the magnet, its dimensions are measured to the magnet size and shape it accommodates. We use disc-shaped neodymium magnets that present stronger flux given their unit size, but magnet shapes can be used using our design editor introduced later.

4.3 Processing Parameters for Fabrication

4.3.1 Material Choice: Initially, we used PLA, the most common material in the field, but its brittleness led to breakage at corners and edges during repeated vibrations and energy harvesting. Simulations (See Figure 10) showed high stress at the spring's endpoints, causing these failures. To address this, we tested more ductile materials, selecting commercially available PETG, ABS, and TPU filaments known for flexibility. Printability was a key factor in material choice. PLA offers the best resolution, while TPU is harder to print due to its stretchability, which leads to sagging and insufficient tension. ABS has high shrinkage during cooling, causing spring lobes to touch. PETG provided the best balance of durability and stiffness, with manageable stringing or oozing through proper print settings discussed later.

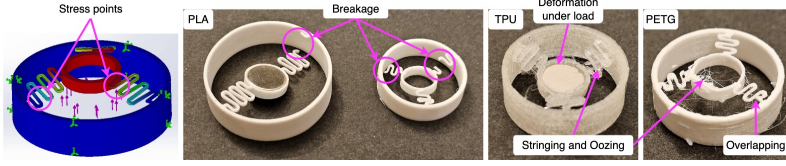


Fig. 10. Different materials present varying printing-related issues, while PETG best responds to parameter fine-tuning for optimal printability, performance, and durability.

4.3.2 Printing Parameter Settings: Different printers utilize varying templates for settings such as layer height, infill pattern and density, and print speed. Optimizing the geometry design for FDM, these parameters can be tuned and controlled through slicer software for successful printing.

Top/Bottom Infill Pattern: Default slicer settings use rectilinear top/bottom layers, but diagonal lines can reduce bed adhesion in spring loops and weaken tensile strength due to discontinuities. They may also overlap adjacent loops and walls. Using a concentric infill improves bed adhesion, structural integrity, and precision by allowing continuous one-line printing of the spring and its shells, resulting in a coherent print and reduced overlap.

Layer Height: In default printing configurations, 0.4mm nozzles typically pair with a 0.2mm layer height, leading to a z-lift of about half the nozzle diameter per layer. This setup usually provides sufficient extrusion volume for each layer. However, if the spring depth is an odd number (e.g., 0.5mm), it leaves a 0.1mm discrepancy after two layers. To achieve greater precision, a finer layer height of 0.1mm is recommended. Although this may increase printing time, it ensures accuracy for both odd and even spring depths and enhances structural integrity through additional z-axis iterations. While first layers are often printed at 150–200% of the set layer height to improve bed adhesion [2], this variation can compromise dimensional consistency and structural integrity. We therefore recommend matching the first-layer height to the subsequent 0.1mm layers for more accurate and reliable spring fabrication.

Extruder Settings: Travel, Retraction, Wiping. Thin flat springs in miniaturized harvesters are prone to stringing and oozing, which create filament bridges, uneven spacing, and surface roughness, reducing flexibility and structural integrity. These defects can lead to deformation or breakage under load. Optimizing extruder settings is therefore critical: travel settings reduce filament dragging, while retraction and wiping minimize leakage and ensure clean deposition. Appendix 1 provides optimal settings, with a full CURA profile available at <https://vib3d.vercel.app/>.

5 Applications: Sensing Vibrations for Context-aware Interactions

VIB3D modules exploit vibration frequency, amplitude, phase, and harvested energy for versatile, low-cost, self-powered sensing. Frequency detection identifies device operation, such as compressor activity; amplitude reflects activity intensity, such as walking versus running; phase captures state changes through directional force shifts, such as toggling a light switch; and harvested energy can indicate interaction frequency and duration. These properties offer high-fidelity yet lightweight alternatives to complex sensors. In this section, we present sensing contexts enabled by VIB3D's ability to capture physical human-object interactions through vibrations.

5.1 Activity Monitoring : Quantity and Quality

Many human activities are a significant indicator of health and safety and can be monitored through vibrations, such as sleep patterns captured at a mattress or physical activity via wearable devices like a shoe-mounted VIB3D module (Figure 11a). *Walking* and *running* induce different amplitudes,



Fig. 11. A VIB3D module mounted (a) on a shoe harvests step-generated energy, increasing from walking to running, and (b) on the floor distinguishes walking (low-voltage) from falls (voltage spike).

producing varying energy levels ($\sim 1V$ vs $\sim 1.5V$), describing the intensity of the workout. These interaction-driven signals can be integrated with mobile and wearable systems; for example, wrist-worn modules can capture repetitive motion patterns (e.g., arm swings) for rehabilitation feedback, where smartphones or BLE-enabled devices receive periodic updates for personal health tracking, monitoring, and feedback-driven interventions without continuous sensing or frequent charging.

Similarly, when mounted on the floor, VIB3D module detects vibrations from activities, such as *regular walking* or *sudden falling*. Walking creates rhythmic, low-voltage patterns ($\sim 80mV$), while falls generate sharp spikes ($\sim 180mV$) (Figure 11b), functioning as a self-powered sensor for multiple uses: monitoring regular daily activities or detecting falls in an independent senior living by remote families to alert emergencies, monitoring foot traffic in smart homes to control lighting or HVAC, supporting security by distinguishing disturbances, and tracking occupancy in commercial spaces for space or maintenance optimization.

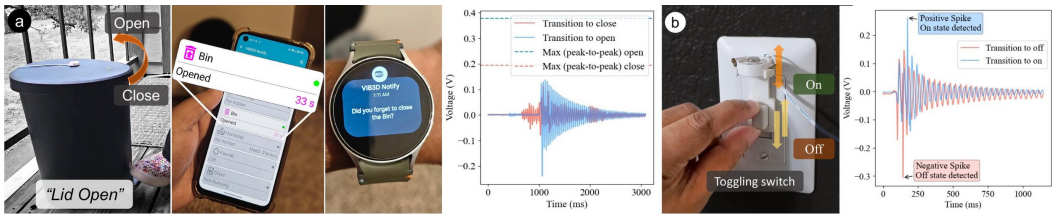


Fig. 12. A VIB3D module (a) on a trash bin detects lid state from voltage differences that triggers a reminder and (b) on a switch detects position from phase changes during toggling.

5.2 State Sensing

State sensing identifies active or idle devices through vibration patterns, such as water flow from a running faucet (Figure 1h). VIB3D can detect the state of the moving part of an interaction: for example, switch toggling produces direction-specific vibration patterns from magnet inertia, enabling on/off detection from positive and negative voltage spike for non-smart switches (Figure 12b). Object states provide additional context, such as whether a trash bin lid is open or closed; pedal activation ($\sim 195mV$) and gravity-driven closure generate different amplitudes ($\sim 385mV$) (Figure 12a), allowing a connected app to trigger reminders for hygiene and contamination prevention. Direction-sensitive vibration patterns can also capture state transitions in mobile interactions such as pulling vs. pushing, lifting vs. placing, or sliding in opposite directions generate distinct signatures, enabling detection of interaction direction.

5.3 Passive Sensing and Target Identification

Objects resonate at distinct frequencies, enabling identification of materials such as metal, wood, or rubber: metal surfaces vibrate at higher frequencies due to their density and stiffness, wood vibrates over a wide spectrum, and rubber resonates at lower frequencies. We tested two VIB3D modules—one tuned low, one high (Figure 13a)—on different surfaces. The high-frequency module responded most to metal, both responded to wood, and the low-frequency module to rubber, as reflected in output voltages. The controller analyzes these patterns to identify surfaces. This capability extends to mobility and accessibility contexts. For example, when integrated into a mobility aid such as a white cane, the module can capture vibration feedback from ground contact to distinguish surface types or obstacles. Such passive sensing can support visually impaired users by providing contextual awareness of terrain changes (e.g., transitioning from pavement to grass or detecting obstacles) without requiring cameras or power-intensive sensing.

5.4 Event Detection

As evidenced in the activity sensing, everyday events like door closing or knocking generate vibrations that reveal user activity and can be harnessed as a cost-effective, self-powered sensing source. Unlike conventional IMU-based devices that draw constant standby power, VIB3D module (Figure 13b) harvests energy to keep BLE devices in deep sleep, waking them only on events to save power. Frequency spectra show both events share similar patterns, but with lower amplitude for knocks ($\sim 200mV$) and higher for closing ($\sim 700mV$), allowing both event detection and classification. These event-driven signals also arise in mobile settings, where device–environment interactions produce distinct vibration signatures. For example, a bicycle or scooter passing over bumps, road irregularities, or braking events produces transient vibrations that can be captured by a VIB3D module. These signals can enable low-power event detection for ride quality monitoring, terrain classification, or safety alerts, while remaining energy-efficient by activating only upon meaningful interactions rather than continuous sensing.

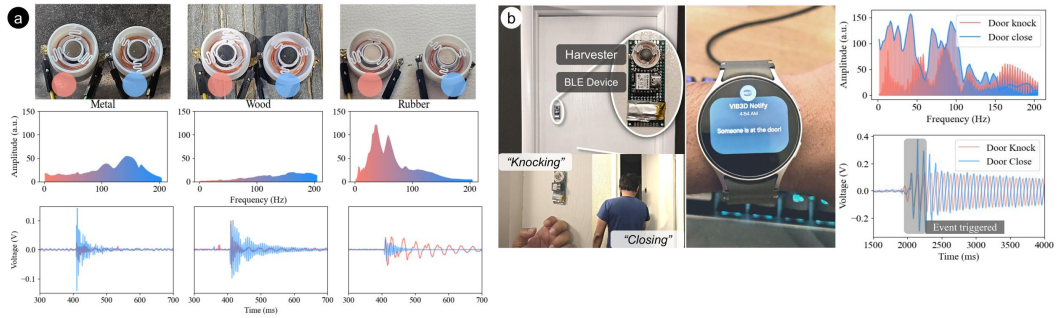


Fig. 13. (a) Two VIB3D modules tuned to low and high frequencies capture distinct responses for metal, wood, and rubber; (b) a module on a door distinguishes knocking and closing via output voltage differences.

5.5 Context Detection

Vibrations from household appliances and infrastructure can support energy usage profiling and environmental sensing. Appliances such as refrigerators and HVAC systems produce sustained operational vibrations that reveal usage patterns and energy efficiency. AC compressor vibrations, in particular, can indicate energy consumption patterns and building occupancy trends (Figure 14a).



Fig. 14. A VIB3D harvester mounted (a) on an AC compressor captures operational vibrations, accumulates energy, and transmits Sozu beacons [53], with the vibration spectrum revealing characteristic frequency; and (b) on a dryer captures vibrations to distinguish loaded and unloaded states from signal energy.

Improving dryer energy efficiency is another benefit of context detection by inferring whether it is running at full load. As shown in Figure 14b, a VIB3D module mounted on the dryer detects vibration intensity to estimate load level, with a moving-average low-pass filter applied to raw voltage data to reduce harmonic noise. The system can then notify users when the dryer is underloaded by comparing the signal energy, encouraging fuller loads for improved energy efficiency. A similar principle applies to scenarios where relative load changes—such as a loaded vs. unloaded backpack while walking—alter vibration intensity and can provide coarse cues about carried weight.

5.6 Performance Monitoring

Home appliances such as compressors, refrigerators, and pumps require vibration monitoring to maintain performance. For example, AC compressors typically vibrate between 75–120Hz, with degradation increasing vibration over time. Battery-powered monitors are costly, but a VIB3D module can harvest energy directly from the compressor. As shown in Figure 14a, the harvester charges a storage capacitor and, once the voltage exceeds 1.5V, triggers a Sozu tag [53] to transmit signals to an SDR receiver. Frequent triggers can indicate intense operation during hot weather or rising vibration levels due to component wear.

5.7 Behavior Tracking

Behavioral patterns can be inferred from vibrations in daily routines, such as water usage. A VIB3D module on a faucet distinguishes opening and closing through amplitude changes—handle movement and flow increase amplitude, while closing reduces it—and tracks duration to trigger alerts for excessive use (Figure 15).

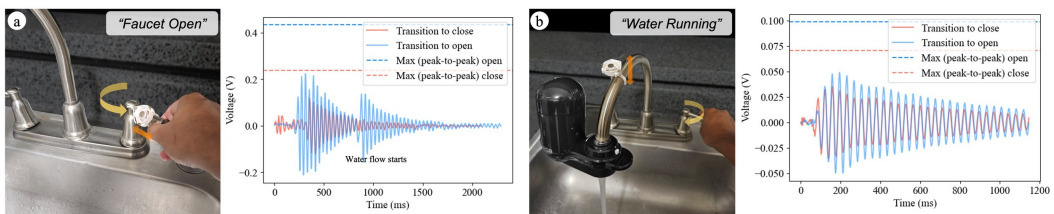


Fig. 15. A VIB3D module mounted on a faucet handle (a) or top (b) detects open/close actions via distinct voltage levels, enabling alerts if left running for extended periods.

Healthy routines such as hand-washing and tooth-brushing can also be tracked. Each soap pump induces vibration that generates voltage, enabling press-count and refill monitoring (Figure 16a), while toothbrush-mounted modules capture motor or brushing vibrations to track duration and

ensure routine compliance (Figure 16b). Through miniaturization, lid opening and closing detection in a trash bin can be adapted to a medicine bottle to monitor intake habits and send reminders when doses are missed. Similarly, a module embedded in a water bottle can track drinking frequency through cap-opening events, supporting daily hydration monitoring.

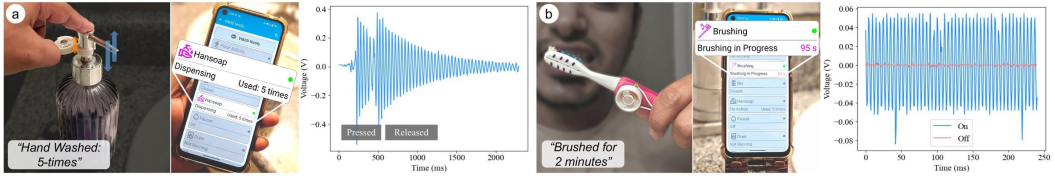


Fig. 16. (a) A VIB3D on a soap dispenser tracks each pump via voltage changes; (b) on a sonic toothbrush, it captures motor and brushing vibrations to monitor patterns and reminders.

Appliances and activities exhibit distinct vibration patterns [33, 42], enabling both activity detection and energy harvesting. Constant-speed machinery (e.g., compressors at 4–20 Hz, pumps at 5–25 Hz, HVAC at 7–40 Hz) produces stable signals, while building-scale vibrations are weaker (e.g., $\sim 10^{-4}$ in) and foot traffic ranges from 0.5–6 Hz with amplitudes around 10^{-5} inches. Everyday interactions such as knocking or clapping generate stronger, more distinguishable signals, whereas low-amplitude events (e.g., key-lock/unlock) approach the sensing limits. Capturing such nuances requires scaling the magnetic field strength: by Faraday’s law ($V \propto \frac{d\Phi}{dt}$), low-amplitude motion produces small flux variation Φ and thus low induced voltage; increasing magnet size/strength raises flux density and its gradient across the coil, improving $\frac{d\Phi}{dt}$ and signal magnitude, which in turn requires scaling the geometry for stable operation.

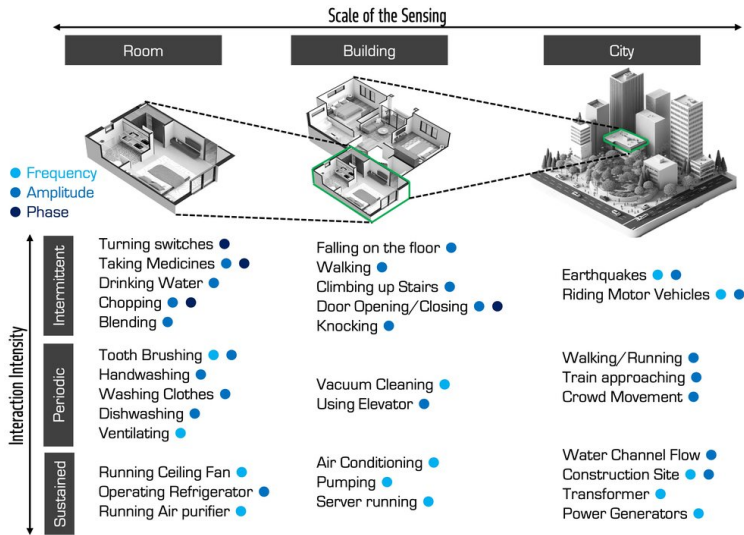


Table 1. Vibration sensing contexts across scales and interaction intensities.

Table 1 summarizes detectable contexts, highlighting that sensing capability is primarily bounded by vibration amplitude and frequency, and that harvester design must be scaled accordingly (e.g., smaller harvesters for low-amplitude but high-frequency interactions like toothbrush use).

6 User Walkthrough: From Identifying Target to Low-cost 3D Printing

Designing harvesting modules for suitable vibration sources typically demands domain expertise, limiting everyday users. We introduce an end-to-end toolkit that lowers these barriers by guiding users from sensing needs to deployable 3D-printable solutions (Figure 17). It integrates three parts: a vision-language model (VLM)-powered design editor, a mobile app for vibration data collection and annotation, and a companion app for real-time feedback.

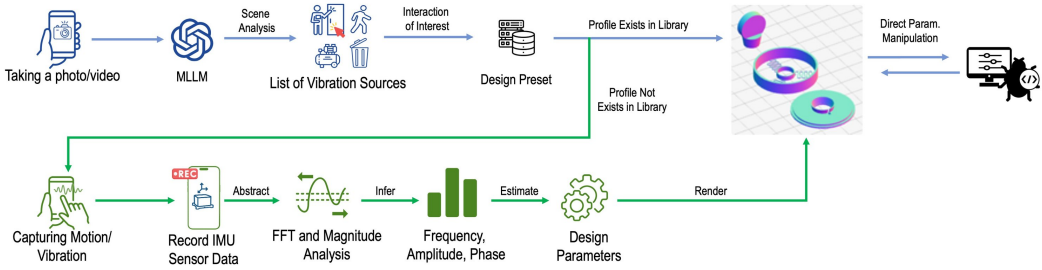


Fig. 17. Overview of the design process. User can discover potential sources by capturing an image of the target or environment, obtain data-driven design by recording vibration data, or perform manual design by directly adjusting parameters.

6.1 Visual Affordance Prediction

The VIB3D editor (Figure 18) is the central interface, guiding users from identifying objects and interactions to auto-generating fabrication-ready harvester designs. Drawing on recent advancements in VLM, VIB3D interprets images to locate potential vibration sources, target objects and contexts, and suggest design parameters. Users have various design options of (i) uploading an image, (ii) reusing typical vibration data of known objects, or (iii) adjusting parameters directly (Figure 17), allowing novices and experts to create readily deployable harvesters.

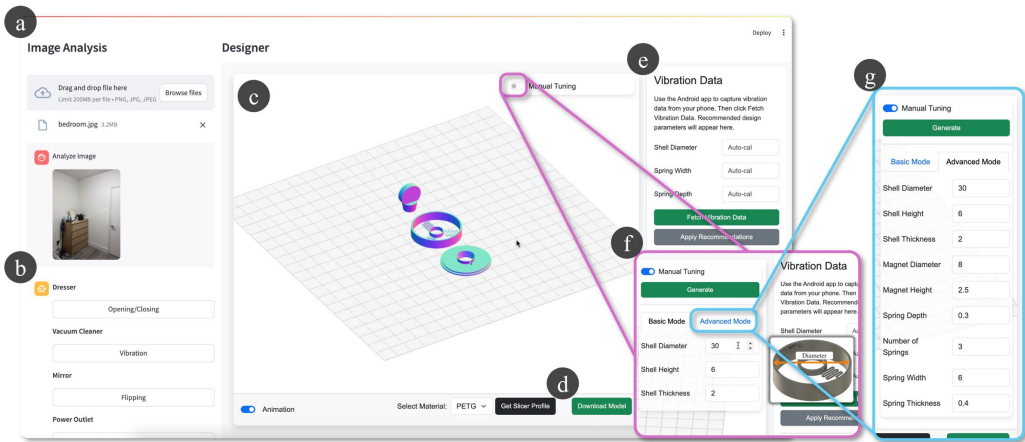


Fig. 18. (a) Image analysis interface for (b) identifying target objects and their associated interaction types. (c) 3D model preview of the designed vibration harvester. (d) Export options for slicer profile and STL file. (e) Vibration data fetch panel. (f) Basic and (g) Advanced mode for manual tuning of the design parameters.

6.1.1 Auto Detection of Interaction Types: To assess whether objects can support self-powered sensing, users upload an image of a single object or a cluttered scene containing multiple candidates (Figure 18a). A locally hosted VLM (Llama3.2-Vision), using Ollama and accessed via LangChain with engineered prompts, analyzes the image and returns interactive objects with plausible vibration-generating actions (e.g., *twisting*, *pressing*, *pushing*, *pulling*, *flipping*, *opening/closing*, *sliding*, and *knocking*) but exclude decorative items (Figure 18b). These results appear as selectable buttons linked to design presets; choosing one applies parameters to generate the VIB3D module. VIB3D features 12 known targets, including metal and wooden doors, drawers, cabinets, compressors, refrigerators, switches, floors, shoes, faucets, and tables, with predefined vibration profiles to generate customizable parameters and print-ready harvester design.

6.1.2 Fetching Vibration Profile from Objects. While VIB3D provides presets for common objects, a vision–language model can generalize to novel interactions. When image-based inference is insufficient, the editor connects to a companion mobile app that records real-world vibration data using a smartphone’s IMU. FFT is applied to extract dominant frequencies, and with multiple recordings, amplitude and phase are analyzed to estimate key design parameters—shell diameter, spring width, and spring depth (Section 4)—for module generation.

6.1.3 Design Tuning: For users seeking fine-grained control, a manual tuning mode is available (Figure 18f–g). In basic mode, users can adjust essential parameters, such as shell size and thickness. Advanced mode exposes full customization, including magnet dimensions, number of springs, spring width, depth, and thickness.

6.1.4 3D Visualization and Model Export. The interface displays a 3D model preview of the harvester (Figure 18c). Users can select material types (e.g., PETG) to obtain the slicer profile, and export STL files ready for 3D printing (Figure 18d).

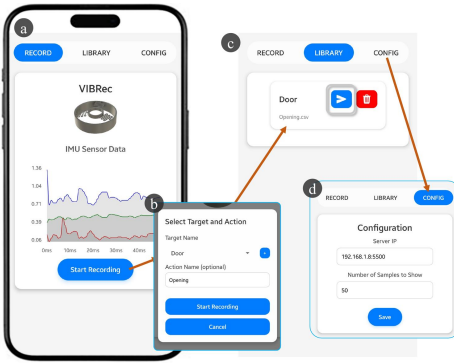


Fig. 19. VIBRec app interface consists of: (a) real-time IMU visualization and recording, (b) object–action tagging, (c) saved-recording library with backend upload and deletion, and (d) configuration settings.

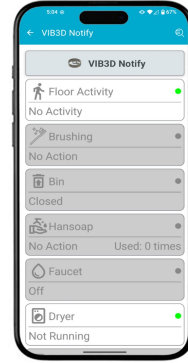


Fig. 20. VIB3D Notify app provides an interface for real-time behavior monitoring, connecting to VIB3D modules via BLE to display the status of various tracked objects.

VIBRec complements the VIB3D editor when presets or image-based inference are insufficient. Built in React, it uses a smartphone’s IMU to capture in situ vibration profiles (Figure 19). Users tag objects and interactions (e.g., “Opening”) and record sessions with real-time x/y/z acceleration, generating labeled data for analysis (Figure 19b). Recordings are stored locally and sent to the backend with a single tap, where vibrations are profiled, design parameters are estimated, and

a print-ready module is generated (Figure 19a–c). As a portable system, VIBRec can extend to Android-based wearables such as watches and rings.

6.2 VIB3D Notify: Real-Time Interaction, Event, Personal Practice Monitoring

VIB3D Notify (Figure 20) is a React-based Android app that connects to VIB3D modules over BLE. It provides a live dashboard of tracked objects and classifies interactions from vibration features such as amplitude and frequency. The app and editor will be open-sourced on the project website.

7 Validating Harvester Performance

The efficiency of a coil and magnet-based energy harvester depends on the strength of the magnets, the number of turns in the coil, the frequency of vibration, and the precision of the mechanical design to keep the magnets and the coil in place with the correct alignment through iterations. We first ran experiments to estimate the effect of different parameters on the resonating frequency of the harvesters. This allows us to determine the settings of the harvester for a specific target object and application. Then we validate the power and energy generation.

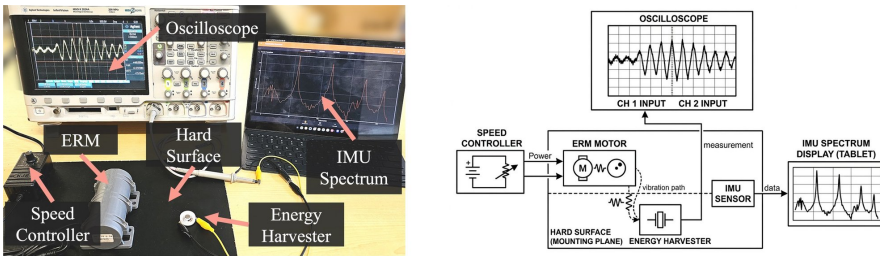


Fig. 21. Experiment setup where an ERM vibrator induces vibrations on a hard surface supporting the modules, while a speed controller varies frequency, an IMU analyzes FFT, and an oscilloscope displays output voltage.

7.1 Effect of Fabrication Parameters

We evaluated harvester performance across design configurations by mounting the harvester on an ERM (Eccentric Rotating Mass) vibrator to simulate real-world frequencies. An IMU captured FFT measured vibration profiles, while an oscilloscope captured output voltage to assess energy conversion (Figure 21). We tested how spring depth affects stiffness and resonant frequency while fixing width (4 mm), thickness (0.4 mm), and shell radius (10 mm), using 8 mm × 2 mm neodymium magnets. Three harvesters per depth were printed in PLA and PETG, with three trials each (nine data points). Greater depth increased stiffness and thus resonant frequency (Figure 22a).

Spring depth below 0.3 mm caused print failures and weak structures. Adding a second magnet lowered resonant frequency by $0.7\times$ due to added mass. To refine tuning, we varied spring width at fixed depth (0.5 mm): wider springs lowered frequency (Figure 22b). We also adjusted spring length by changing shell diameter (2.5–4.5 cm), computing effective length by excluding magnet and rod dimensions. Shorter springs increased frequency, while larger harvesters allowed longer springs and bigger magnets, boosting output but at the cost of larger size (Figure 22c).

7.2 Generated Power

To assess generated power, we varied magnet size, number of magnets, and coil turns. Vibrations were induced using an ERM vibrator, and output voltage was recorded via an oscilloscope under controlled excitation. Oscillatory magnet motion produces sinusoidal voltage and current, with

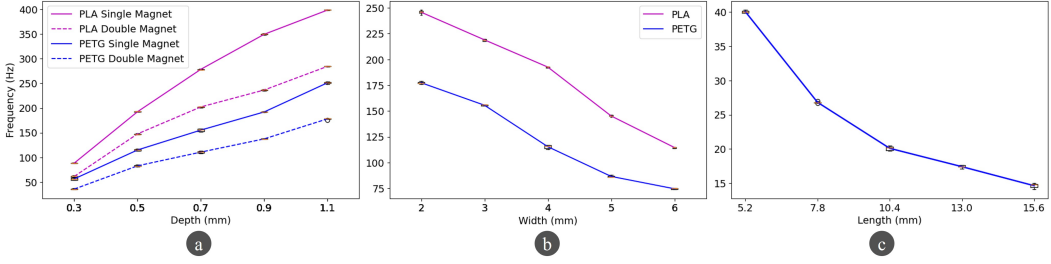


Fig. 22. Resonating frequencies across different configuration. (a) Resonating frequency vs spring depth of the modules, (b) resonating frequency vs width of the spring, and (c) resonating frequency vs spring length.

power estimated as $P = V_{rms}^2 / R_l$, where R_l is the load resistance and V_{rms} is the measured RMS voltage. For a peak voltage V_p , $V_{rms} = V_p / \sqrt{2}$. Piezoelectric harvesters suffer from high output impedance (typically hundreds of $k\Omega$ to $M\Omega$), which limits current and applying a small load resistance attenuates voltage and reduces power output. By contrast, the VIB3D coil operates in the Ω range, allowing the use of relatively small load resistances (high load). While precise load optimization remains an electronics problem, we use 100Ω in our experiments.

7.2.1 Effect of Number of Coil Turns. According to Faraday's law, induced voltage is proportional to the number of turns. We used 0.1 mm magnet wire and evaluated 50, 75, 100, 200, 400, and 800 turns. Two trends were observed: (i) increasing turns raises output voltage, and (ii) it also increases coil resistance (Figure 23a). In practice, 200–400 turns provide sufficient voltage for sensing, while 800–1200 turns are required for effective energy harvesting.

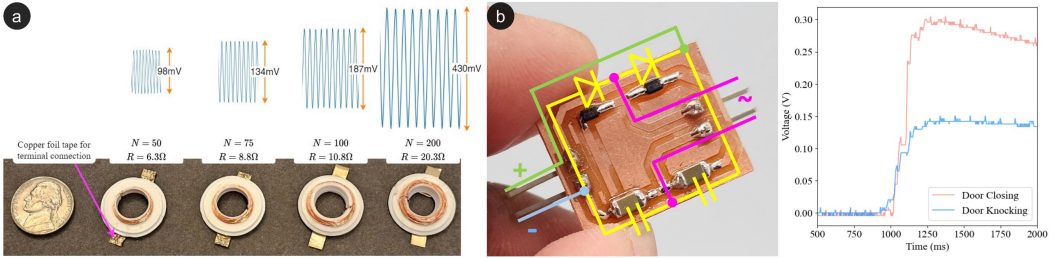


Fig. 23. (a) Coils with different numbers of turns and corresponding voltage output and resistance values. (b) Delon voltage-doubler rectifier and accumulated voltage from door knock and door closing actions.

7.2.2 Effect of Number of Magnets. Magnetic flux strength and coil turns jointly determine harvester output. We use disc-shaped neodymium magnets for their high flux density. Increasing the number of stacked magnets produces two effects: (i) it shifts system dynamics and resonant frequency, and (ii) it increases induced voltage by strengthening the magnetic field. However, scaling is limited: the combined flux does not increase linearly, and added mass reduces the mechanical stability of the flat spring. In our experiments, stacking more than three magnets exceeded these limits.

7.2.3 Power Delivery and Usability. For a VIB3D module with a 20 mm diameter, 200-turn coil, and 0.3 mm flat spring depth with three magnets, we measured 430mV peak-to-peak, 152.1mV RMS, and 0.231mW (Figure 24a), sufficient for self-powered sensing and RF-based event logging [5, 53].

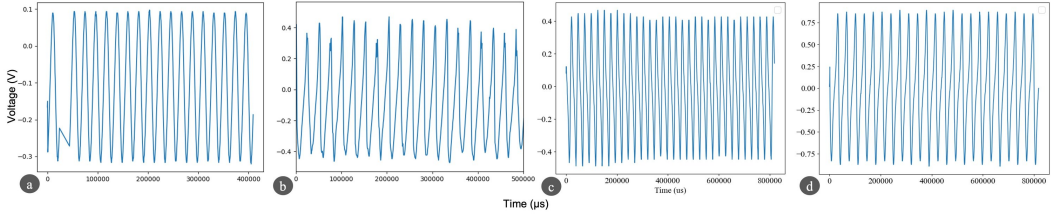


Fig. 24. Output voltage waveforms of VIB3D modules: (a) 20 mm module with a 200-turn coil and three 8 mm magnets, (b) 30 mm module with a 400-turn coil and two 10 mm magnets, (c) 30 mm module with an 800-turn coil and one 10 mm magnet, and (d) 30 mm module with an 800-turn coil and two 10 mm magnets.

Scaling to a 30 mm module with two 10 mm neodymium magnets and a 400-turn coil produced 0.998V peak-to-peak, 0.3529V RMS, and 1.245mW (Figure 24b). Increasing to 800 turns achieved similar output with a single magnet (Figure 24c), and with two magnets reached 1.785V peak-to-peak (0.6315V RMS), delivering $\sim 4mW$ (Figure 24d).

In practice, the generated sinusoidal voltage must be rectified for energy storage and use, reducing effective output. A Schottky bridge (with a $\sim 0.2V$ drop in each diode) incurs a $\sim 400mV$ loss; although ICs such as LTC3109 can mitigate this, we use a simpler Delon voltage doubler, effectively halving diode-related losses. Figure 23b shows stored energy across a 100 μF capacitor: a door-knock stores $\sim 0.154V$ (1.2 μJ), while door-closing stores $\sim 0.308V$ (4.7 μJ). A simple voltage threshold allows the classification between these two activities. Beyond accumulation, this rectification preserves amplitude differences, enabling distinction between everyday activities.

Apart from acting as a self-powered sensor, accumulating small energy into a storage (e.g., supercapacitor) is also possible for the occasional need for relatively larger power needs such as updating e-ink display [4]. In addition to powering itself, this is sufficient for harvesting and powering devices such as a light sensor (MAX44007, 2.15 μW), a CO sensor (TIDA00756, 3.21 μW), a temperature and humidity sensor (DHT22, 0.132–3.3 mW), or a PIR sensor (BOOSTXL, 8.58 μW). By accumulating this energy, it can also fully support the periodic operation of low-power microcontrollers such as the nRF52840 (4.5 μW –19.2 mW) or the nRF52832 (5.7 μW –16.2 mW).

7.3 Durability of the Mechanism

To evaluate structural resilience, we conducted stress tests using a 60 W ERM vibrator at 2500 rpm. Results revealed clear differences across materials and magnet configurations. PLA harvesters proved fragile: a single-magnet configuration failed within 2 minutes, and assemblies with multiple magnets broke in less than 10 seconds due to increased load and brittleness. In contrast, PETG harvesters demonstrated substantially higher durability, sustained intensive vibration for 45 minutes without failure with up to three magnets. However, with four or more magnets, even PETG failed within 1–2 minutes, establishing an upper load tolerance limit.

To relate the stress test to real-world interactions, we recorded door-closing and door-knocking vibrations using a 240 fps high-speed camera. A single door-closing event generated approximately 42 oscillations, while a single door-knocking event generated approximately 19 oscillations. As the ERM motor used for durability testing operated at 2500 rpm for 45 minutes, it corresponds to approximately 112,500 vibration cycles. Using a cycle-based comparison, this stress test is roughly equivalent to approximately 2,679 door-closing events or 5,921 door-knocking events. Notably, the ERM produced vibration amplitudes several times higher than typical everyday interactions, making this a more aggressive loading condition. The PETG structure remained intact after the

test, suggesting that the printed harvester can withstand repeated interaction-induced vibration under everyday-use conditions.

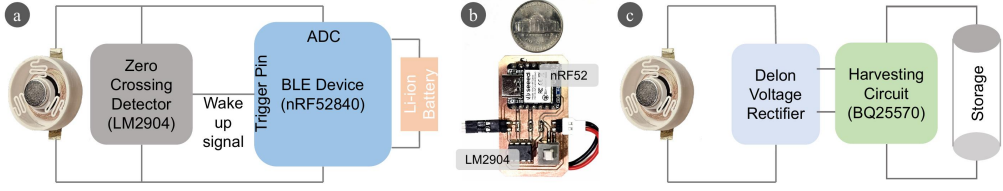


Fig. 25. (a) VIB3D as a self-powered sensor triggering a BLE device via Zero Crossing Detector, (b) fabricated circuit, and (c) energy harvesting and storage for fully self-powered devices.

7.4 Self-Powered Sensing and Energy Harvesting with VIB3D Modules

VIB3D modules can act as self-powered sensors or harvest energy for fully self-sustained systems. Figure 25a shows a configuration where the module is integrated with a Zero Crossing Detector (LM2904) to generate a wake-up signal for an nRF52840 BLE device, which remains in deep sleep. Upon activation, the device wakes, captures ADC data, processes it, transmits a notification, and returns to sleep (Figure 25b), enabling energy-efficient operation.

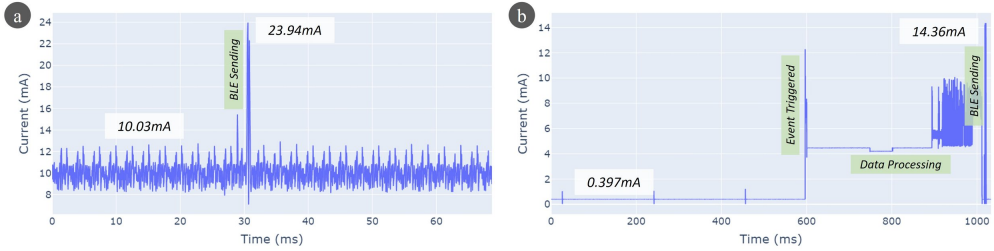


Fig. 26. Current consumption of (a) the IMU-based system (10.03 mA idle, 23.94 mA peak during BLE transmission), and (b) the VIB3D-based system (0.397 mA idle, 14.36 mA peak during BLE transmission).

We compared this approach with an nRF52840 paired with an MPU6050 IMU for detecting floor movements. Using the Nordic Power Profiler Kit II, the IMU system consumed 10.03 mA in idle mode and peaked at 23.94 mA during BLE transmission (Figure 26a), whereas VIB3D consumed 0.397 mA in idle mode and peaked at 14.36 mA (Figure 26b). This reduction can extend operation from 15 days to over a year. While IMUs capture complex 3D vibrations, many everyday interactions require simpler event-level sensing, which VIB3D enables more efficiently using harvested vibration. Figure 25c illustrates the energy harvesting topology, where vibration energy is rectified using a Delon rectifier and managed by a BQ25570 harvesting circuit to charge a supercapacitor.

Figure 27a shows RF signals broadcast from a Sozu tag powered by a VIB3D module attached to an outdoor HVAC compressor, captured using an RTL2832 SDR device. A shift in the vibration intensity modulate the harvested energy and, in turn, the transmission behavior. A similar setup on a shoe (Figure 27b) shows that walking produces lower voltage than running, leading to corresponding shifts in transmission frequency ($\sim 48.8\text{MHz}$ to $\sim 49\text{MHz}$) due to the tag's voltage dependence. These differences enable activity classification; empirically, walking required about five steps per broadcast, while running required about three. While combining both topologies to reduce idle power loss in self-powered sensing is feasible, it remains beyond the scope of this work.

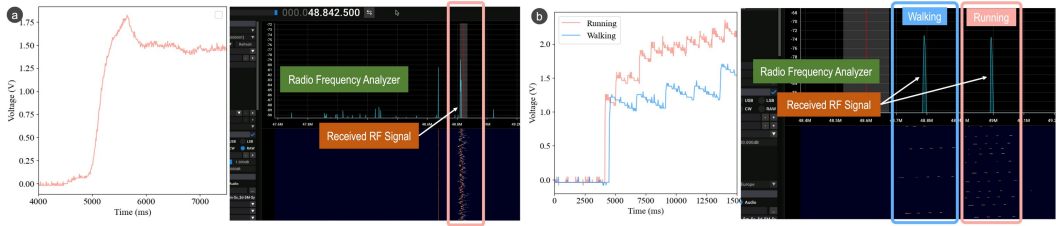


Fig. 27. A VIB3D module paired with a Sozu tag [53] broadcasting radio signals: (a) attached to an HVAC outdoor compressor unit, and (b) mounted on a shoe to capture walking and running activities.

8 Discussions & Future Work

8.1 Mobile and On-the-go Outdoor Deployment

Due to its scalability, VIB3D modules can extend beyond fixed infrastructure to mobile and outdoor, on-the-go contexts where continuous power is limited. Everyday interactions—such as walking with wearables, carrying objects, or vehicle-induced vibrations—naturally generate intermittent energy that supports event-driven sensing. Modules embedded in personal items (e.g., shoes, bags, or tools) can capture motion patterns, detect impacts during transport, or trigger alerts in outdoor environments without relying on batteries.

Material choice becomes critical in such deployments. While PETG offers a practical balance of printability and ductility, materials like ASA provide improved UV and weather resistance for outdoor exposure but warps during fabrication. Polycarbonate offers high strength and temperature resistance for harsh environments but requires higher processing temperatures and is difficult to print for thin geometries. Nylon provides superior flexibility and fatigue resistance (elongation at break up to $\sim 300\%$), making it suitable for repeated deformation, but its moisture sensitivity and dimensional instability complicate fabrication. These challenges can be mitigated through controlled fabrication setups (e.g., enclosed printing, tuned print profiles, and material conditioning), but introduce additional complexity. Thus, material selection must balance durability with manufacturability, especially for thin spring-based designs.

8.2 Vibration as an Actuator Source

A potential extension of the harvester is its use as an actuator while retaining self-powering capability. By reversing the energy conversion process, it can convert electrical energy into mechanical motion, functioning similarly to a linear resonant actuator. One application is in smart wearables, where a harvester integrated into clothing or accessories captures energy from movement and functions as a haptic actuator. It can provide notifications or directional cues through vibration, enabling multi-functional feedback within a compact design without requiring a separate actuator.

8.3 Event-based Sensing for Intermittent Computing

Energy harvested from VIB3D is small compared to large-scale renewables, making them suitable for minimal operation, such as opportunistic data loggers or event-based alerts [4]. Factors such as vibration amplitude and spectral density limit extractable energy. While insufficient for continuity-critical devices, intermittent computing [20] enables powering distributed devices, complementing dead batteries as shown in prior work (e.g., E3D [4]). Mechanisms are needed to maintain enough standby energy to avoid falling below the turn-off threshold.

8.4 Limitations and Future Work

8.4.1 Hallucinations in Object/Affordance Detection. While the VLM is generally robust for scene analysis, two limitations remain: (i) it occasionally proposes non-vibratory interactions (e.g., mirror “reflection”) or out-of-vocabulary labels, and (ii) it cannot reliably infer material properties from images alone. We plan to incorporate reasoning-augmented VLMs and material-aware sensing to improve affordance understanding and automatically generate more reliable vibration profiles.

8.4.2 Placement, Coupling, and Calibration. VIB3D relies on mechanical coupling between the harvester and the vibrating object. As a result, placement, orientation, attachment stiffness, and object geometry may affect both harvested energy and sensed vibration profiles. While our examples demonstrate that users can tune harvesters for specific objects and interactions, broader deployment may require placement guidance, lightweight calibration, or adaptive profile updating across users, objects, and environments.

8.4.3 Capturing Richer and Broader-Spectrum Vibrations. The current harvester uses a single bottom-mounted coil and primarily captures vertical oscillation along the magnet axis. Real-world sources, however, often exhibit multi-dimensional and broadband motion. Future designs could use multi-axis coils to capture additional degrees of freedom, as well as spring geometries with varied widths or loop configurations so that different sections resonate at different frequencies. These extensions could improve energy capture and enable richer gesture and context sensing, though they also introduce additional fabrication and assembly complexity.

8.4.4 Expanding Vibration Features for Context-Aware Sensing. Our current sensing pipeline focuses on frequency, amplitude, and phase as effective features for distinguishing everyday interactions. Additional temporal and spectral features may further improve versatility. For example, duration and temporal segmentation could support usage-frequency logging, modulation patterns could reveal shifts in amplitude or frequency for structural health monitoring, and waveform shape, harmonics, or higher-order spectral features may help distinguish objects with similar spectra, such as identical compressors. We leave these extensions for future work.

8.4.5 Long-Term Robustness and Deployment. Although VIB3D is designed for low-cost FDM fabrication, long-term deployment may introduce wear, deformation, or alignment drift in the printed spring and magnet-coil assembly. Future work should evaluate durability under repeated vibrations, environmental variation, and extended use to better understand when fabricated harvesters can serve as reliable batteryless sensing infrastructure.

9 Conclusion

VIB3D offers a scalable approach to sustainable, self-powered sensing. Its adaptability enables custom designs that convert ambient vibrations into usable energy across diverse applications. By democratizing fabrication, this work supports broader adoption of energy harvesting technologies. We share our designs for community-driven development at <https://vib3d.vercel.app/>.

Acknowledgments

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Appendix

1. Slicer Settings

Table 2. Recommended Slicer Settings for VIB3D Module Printing.

Slicing Setting	Value	Slicing Setting	Value
Travel Speed	35 mm/s	First Layer Speed	20%
Retraction Distance	3.5 mm	Retraction Speed	35 mm/s
Wiping Distance	2 mm	Wiping Speed	35 mm/s
Layer height	0.1 mm	First Layer Height	0.1mm
Ironing	Off	First Layer Acceleration	600mm/s ²