MiniKers: Interaction-Powered Smart Environment Automation

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Automating operations of objects has made life easier and more convenient for billions of people, especially those with limited motor capabilities. On the other hand, even able-bodied users might not always be able to perform manual operations (e.g., both hands are occupied), and manual operations might be undesirable for hygiene purposes (e.g., contactless devices). As a result, automation systems like motion-triggered doors, remote-control window shades, contactless toilet lids have become increasingly popular in private and public environments. Yet, these systems are hampered by complex building wiring or short battery lifetimes, negating their positive benefits for accessibility, energy saving, healthcare, and other domains. In this paper we explore how these types of objects can be powered in perpetuity by the energy generated from a unique energy source – user interactions, specifically, the manual manipulations of objects by users who can afford them when they can afford them. Our assumption is that users' capabilities for object operations are heterogeneous, there are desires for both manual and automatic operations in most environments, and that automatic operations are often not needed as frequently – for example, an automatic door in a public space is often manually opened many times before a need for automatic operation shows up. The energy harvested by those manual operations would be sufficient to power that one automatic operation. We instantiate this idea by upcycling common everyday objects with devices which have various mechanical designs powered by a general-purpose backbone embedded system. We call these devices, *MiniKers*. We built a custom driver circuit that can enable motor mechanisms to toggle between generating powers (i.e., manual operation) and actuating objects (i.e., automatic operation). We designed a wide variety of mechanical mechanisms to retrofit existing objects and evaluated our system with a 48-hour deployment study, which proves the efficacy of *MiniKers* as well as shedding light into this people-as-power approach as a feasible solution to address energy needed for smart environment automation.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile devices**.

Additional Key Words and Phrases: Smart environments, Energy harvesting, Automation, People-as-power, Interaction-powered, Self-sustaining computing

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1 INTRODUCTION

Automating objects in physical spaces has long been practiced in ubiquitous computing and the Internet of Things. Automation not only boosts efficiency but also creates environments that can be equally accessible to all. These environments feature physical interfaces on the objects for manipulation or function (e.g., a handle or pedal for movement). Many everyday objects require users with enough dexterity, motor strength, and often the use of both hands to interact purposefully. These requirements can be challenging to someone who is not capable of such interaction due to a physical disability. Thus, automation can be a great benefit for users with motor impairments and even offer much utility to everyone else – for example, if someone has their hands occupied at the moment. Existing approaches (like sliding doors in a supermarket, automatic hand sanitizer dispensers in a building) rely either on tethered power, which limits the flexibility of deployment, or run on batteries demanding maintenance efforts. Both of these power solutions are difficult to scale – which we suspect to be one of the key reasons why we have only seen the success of automation on a few objects while the majority of everyday objects remain passive.

Prior research has tackled the energy challenges on the sensing front [8, 9, 72, 73] while little has been done on the actuating front – specifically in regards to actuating objects with intrinsic motion parameters (e.g., drawers with slides, doors with hinges, etc.). This characteristic is a huge challenge as actuating applications require a large power consumption relative to sensing applications in many orders of magnitude. For instance, we found anecdotally that the amount of energy consumed to open a door once is equivalent to the amount of energy required to sense that event for nearly one whole year.

Fortunately, the remedy can be found in the problem. Electric motors consume energy when actuating objects; however, when used as generator, they are also ideal for harvesting energy from the current generated by the input actuation – the electromagnetic induction effect, which generates more than 93% of all the electricity that powers the world [13]. Our research uniquely leverages this advantage of motors by enabling them to work as both harvesters and actuators seamlessly in a smart environment. Our system intelligently switches between manual and automation modes depending on the user needs in the environment. One existing example of such design concept can be found on the commercially available door closers – energy stored in the spring when the door is being manually opened can later be used to automatically close it, preserving user time while improving environmental safety, achieved with a simple and passive device that can last for years [17]. Though door closers create force/torque overheads that might make it harder to use the door than without, the benefits overcome this potential undercut in usability. We were inspired by examples like this when we created *MiniKers*, which generalize the design concept to a wide array of everyday objects.

This dual usage allows us to explore how we can utilize user interactions as a ubiquitous and reliable source of power. While prior work has demonstrated the efficacy of environment-centric harvesters (e.g., solar cells, wind turbines), we turned our focus to people – a rich source of kinetic energy – because there will undoubtedly be presence of users wherever there are interactive systems, and user interactions can be turned into power as several seminal works have demonstrated [15, 27, 63, 73]. Unlike prior work which focused on interactive sensing, this paper looks into a different and yet important task – actuation via enhancing objects that have intrinsic movements, with motors that can be repurposed into energy harvesters.

We present *MiniKers*, a series of interaction-powered actuation devices for smart environment automation. *MiniKers* can retrofit to everyday objects with various mechanical mechanisms (see Figure 7 for examples) and feature a custom circuit board, energy-aware software, and a phone app. Taking the instrumented window blinds for example, *MiniKers* harvest energy from a synchronously spinning DC motor each time the tilt wand is turned manually. This energy is stored in a supercapacitor and then in a small Li-Po battery. This energy is later extracted from the battery to drive the same DC motor, providing the actuation force that turns the tilt wand and opens/closes the window blinds automatically. The energy harvesting, regulation, and management are controlled by the custom circuit board centered around low-power components including a BLE-enabled SoC (Nordic nRF52832). Simultaneously, our system hitchhikes the energy harvesting mechanism for sensing, turning the harvested energy into sensory feeds. Specifically, by monitoring the amount of harvested energy, *MiniKers* detect the state of objects as well as fine-grained information such as magnitude, speed, and frequency. Overall, our research contributions include:

- Generalization of the design concept which uses people as power for interactive systems by harvesting energy from user interactions (i.e., manual operations) to power automatic operations of everyday objects.
- A custom circuit that uniquely combines sensing, energy harvesting, regulation, management, and energy-aware actuation for an optimal energy efficiency.
- A system that utilizes this custom circuit with various mechanical mechanisms that can cheaply retrofit onto everyday objects.
- A technical validation and a deployment study that assess the feasibility of interaction-powered automation, creating footholds for future work.

2 RELATED WORK

2.1 Motorized Smart Environments

MiniKers are related to systems that actuate users' environments on their behalf, motorizing objects for remote controls or assisted uses. These systems intersect with research and commercial efforts in smart homes, automation, remote control, and personal robots. In the product domain, Clicbot [31], Smartians [60], and Microbot-push [43] use gear mechanisms powered by DC motors to enable remote actuation of everyday objects, mostly small ones like switches. There have also been automatic door closers [17] and greenhouse auto vent openers [55] that actuate objects with only passive mechanisms (i.e., no electronic components). The aforementioned retrofitting devices could result in additional installation labor which can make built-in control mechanisms preferable if the "smarts" could be built from scratch (e.g., smart switch [28] or smart lock [50]).

In the research domain, there have been two common modalities to achieve environment automation. People can either have general-purpose robots which can move around the space for a variety of tasks [6, 7, 18, 19, 30, 32, 67], or robotic mechanisms which can be instrumented onto objects for software-controlled actuation [1, 10, 22, 34–36, 51]. The latter is more closely related to this work. In this realm of innovations, IoTIZER [10] instruments light and aesthetically appealing mechanisms onto objects with a toolkit. Robiot [35] motorizes everyday objects by retrofitting 3D-printed motor mechanisms. Mobiot [1] further mobilizes the objects with 3D-printable structures. In this line of work, Roman [36] enables handheld objects to be manipulable by robotic arms with 3D-printable add-on mechanisms. It is possible to structurally modify everyday objects to augment their default functionalities [22, 34]. Finally, RetroFab [51] offers an authoring tool to scan an existing physical interface and automate its controls by adding external mechanical and electronic components.

2.2 Power from Environments

Energy harvesting has long been exploited by interactive systems and environments in which these systems reside have many types of energy to leverage. One of the most common energy sources is light, harvested by photovoltaic panels. On commercial products, light energy harvesting is often used to extend battery lifetime. These products range from keyboards [39], smart curtains [61] and cleaning robots [26] to trash cans [33], street lights [25] and vehicles [62].

In the research domain, a variety of energy sources have been utilized. Light continues its popularity as a major energy source in ubiquitous computing and IoT, powering systems for ambient displays [20], hand posture reconstruction [37], and touch sensing [65]. It is possible to harvest energy using piezoelectric materials from mechanical oscillations such as vibrations resulting from running motors [73], traffic on road and bridges [46, 66], fluctuations of pressure inside water pipes [9], and even temporal ambient temperature changes [74]. Recent advances in 3D printing also facilitate harvesting such energy using delicate coil-magnet mechanisms that allow the resulting devices to harvest vibrations of minute magnitude that were beyond previously possible [11, 29]. Finally, such oscillations can induce a triboelectric effect that has recently been enhanced by the exploration of nano-level structures, resulting in sensing systems that could be powered by sound, the very signal they aim to sense [2, 4, 38]. Less common are microbial fuel cells (MFC), which have also shown promise in prior work in powering sensing systems [40, 42]. To generalize energy harvesting to a wider set of use cases, prior research has investigated general-purpose platforms and pipelines. For example, Campbell and Dutta [8] proposed a pioneering generic system architecture that runs on energy scavenged from environments to detect events in buildings. The difference between signals that yield energy and signals that need to be sensed often means separations between energy harvesters and sensors. In the HVAC sensing example shown by the prior work [8], light energy has to be harvested from a solar cell on a window delivering energy to the airflow sensor attached to the HVAC vent through a long wire. This configuration might be obtrusive to user environments and undermine the durability. To mitigate this undesirable configuration, prior work looked into energy and signal that can be bundled together. OptoSense [72] proposes a light-sensing pipeline that runs on energy harvested also from light, resulting in a fleet of compact and versatile sensors. In another example, Sozu [73] proposed a general sensing pipeline that leverages the very harvested energy as the signals for sensing, by transforming this energy into RF broadcasts.

2.3 People as Power

Another popular source of power comes from users themselves – people can be leveraged as major sources of energy. This creates an inviting opportunity to address the power constraints on wearable devices [59]. For example, the swaying motion of arms can be harvested by coil-magnet mechanism [68], and mechanical oscillations induced by foot stepping can be turned into energy using an array of piezo discs [71]. Even the seemingly minute thermal energy dissipated by human skin can be turned into electricity using Peltier junctions [48]. It is also possible to combine multiple energy sources, as is shown in Facebit [12], which investigated different types of energy harvested from wearers' faces, including motion, breath, and thermal, all of which can be easy to find at the proximity of masks.

Closer to *MiniKers* is prior work that exploited user interactions with interactive systems and objects around. First, there have been commercial products such as self-powered doorbells [41] and switches [56], which transmit RF broadcasts powered by energy harvested from button presses. In the research domain, The Peppermill [63] demonstrates a self-powered interaction paradigm. In this example, the device allows users to rotate a knob to generate power for sensing user interactions, such as button presses. Similarly, EnergyBugs [53] harnesses electricity generated by children shaking energy harvesters with coil-magnet mechanisms. Using a different class of harvesters, Paper Generators [27] allow power generation from users performing touch, tap, and rub gestures on paper leveraging the triboelectric effect. Recently, Battery-free Game Boy [15] demonstrated an energy-aware gaming platform that uniquely combines energy generation with game actions like button presses. Closest to our work are previous systems that aim to harness energy resulting from user interactions with everyday objects. Among the fleet of examples, one class of devices in Sozu [73] turned user motion (i.e., turning mailbox flags, using pruners, opening/closing pill bottles, drawers, and doors) into RF broadcasts for sensing applications.

3 DESIGN GOALS

Based on our review of existing smart environment automation systems and user expectations as discussed in literature [52, 64], we set several design goals for *MiniKers*, which we achieved in this research:

Rich input: Unlike personal devices, automation in environments has unique challenges to overcome because environments are often shared across multiple users, each having their unique set of capabilities and preferences.

This diversity demands interactive systems in shared environments to accommodate diverse interactions. Ideally, the device should offer a wide array of interaction modalities (e.g., touch interaction, voice control) or even multi-modal interactions to fit user needs. This design goal was drawn from the recent success of commercial smart environment solutions, with which users often have various controls of smart appliances like lights [47], TV mounts [24], window shades [23], and screens [58], using tangible buttons, remotes, apps on smartphone and tablets, or voice.

Compatibility: Practical automation techniques should consider all stakeholders in the environment. Specifically, there needs to be automation that does not compromise the functionality and ergonomics of existing objects. This design concept has been demonstrated in literature [10, 14, 60, 61, 73]. In the context of this project, we aim to have compact and versatile mechanisms that can easily retrofit existing environments. Ideally, the core components (e.g., motors and gears) could be readily applicable to a variety of objects without altering their existing structures and affordances.

Adaptability: Adaptability has been a common feature in smart environment products such as smart lights, thermostats, irrigation systems, etc. that can adjust brightness, temperature, soil moisture using sensory data from the environment. Similarly, our automation system needs to have situational awareness to respond intelligently to a different system and environmental status. For example, the system should adjust intrinsic parameters (e.g., motor current) in response to different energy levels and use frequencies. We achieved this through energy awareness – enabling *MiniKers* to probe energy supply and consumption at key points on the circuit board. We implemented a programmable resistance in the motor powerline and PWM motor drive to adapt the motor current to the system's energy status.

Low cost and durability: Practical automation systems should be low-cost to be scalable. With a house that could easily consist of more than 20 objects to automate, the cost of instrumenting each should not exceed $50, totaling the whole house of automation with $1000, which is comparable to a middle-end smartphone or a laptop. At the same time, lowering the price tag should not be at the cost of durability. The system needs to be robust against exposure to elements (e.g., temperature, humidity, and impact). This design goal has been sought after in previous IoT systems (e.g., [3, 8, 73]). In the following paper, we demonstrate and evaluate how *MiniKers* achieve these with a 48-hour deployment study on 9 objects across 3 locations of different configurations and functionalities.

4 ENERGY INVESTIGATION

Energy harvesting with motors and consumption at motors are at the core of our research. In this section, we conducted benchmark tests aiming to answer one key question: how does the amount of energy harvested from manual operations compare to that of the energy consumed in automatic operations?

4.1 Apparatus

We conducted benchmark tests to investigate amounts of energy that could be harvested from everyday objects as well as the factors that affect them. To conduct these tests with sufficient versatility without losing generalizability, we decided to use a 3D printed device (Figure 1 right). This 3D printed device allowed us to correlate harvested energy with force (in translational motions) and torque (in rotational motions), in forms that are common to find in everyday settings (Figure 1 left). The device can be put into two configurations. The first configuration features a handle that moves in a translational manner while the second configuration features a handle that moves in a rotational manner, both in relation to the device body. The force and torque needed to actuate the device are set by the embedded motors, for which we selected the GA12-N20 DC motor with an additional gearbox attachment.

This type of motor is low-cost and easy to source, because of which they are common to find in maker projects and commercial products.

We conducted three tests below. These tests systematically examined key factors, including motor gear ratio, user motion characteristic, and resistance in the motor powerline. Insights from these tests guided us in various design choices in developing *MiniKers* hardware and firmware as we will elaborate in detail later in Section 5.

Fig. 1. Translational and rotational motions are the two common types of motion on everyday objects (left). The device designed to simulate these motions on everyday objects and used in the energy investigation tests (right).

4.2 Motor Gear Ratio

One immediate factor that affects energy harvesting is the gear ratio of the gearbox, which is the ratio between the angular speeds of the driver (input) gear to the driven (output) gear. Of note that when motors are used as generators, the driven gear is the one that is actuated by user interactions, and therefore the gear ratio becomes the reciprocal of that of motors as actuators. Intuitively, larger gear ratios require a larger force to actuate but can induce a higher amount of energy. We conducted tests to quantify this effect in the context of user-powered mechanisms. In this test, we used motors with gearboxes of different gear ratios (500:1, 250:1, 150:1, 100:1, 75:1) and measured their output currents when these motors were connected in series with a 100 Ohm resistor. These motors were instrumented onto the test device, which was affixed to a lab table with the configuration that supports translational motions. An experimenter actuated the device from one end to the other and returned to the original position (i.e., one trial) three times at normal speeds (similar to ones in actuating everyday objects) during which a force gauge was used to measure force and torque. Figure 3 left shows the results, which verified our expectation that the force required and energy generated are proportional to the gear ratio – motors with larger gear ratios are in general harder to actuate, but can generate more energy which is roughly linearly proportional to the gear ratio.

4.3 User Motion Characteristics

An important factor that affects energy harvesting is the varying user interactions due to the fact that different users often have different motor capabilities, resulting in different speeds, acceleration and deceleration rates, etc. This variance could affect the amount of harvested energy. We conducted a user study (n=5), using the same device in the previous test. A motor with the gearbox of a 250:1 ratio was used. Its output was connected to a 100 Ohm resistor. Participants were asked to complete three trials actuating the device at normal speeds. The output voltage across the resistor was recorded and can be found in Figure 2. Interestingly, we measured a largely consistent amount of generated energy despite that different users manipulated the device at different speeds. However, we found a large difference between the two motion types – translational motions generate more energy than rotational motions due to the difference in the number of revolutions by the motor over the courses of trials. This observation led to the design of having larger gear ratios for rotational motions than translational ones later in our system implementation.

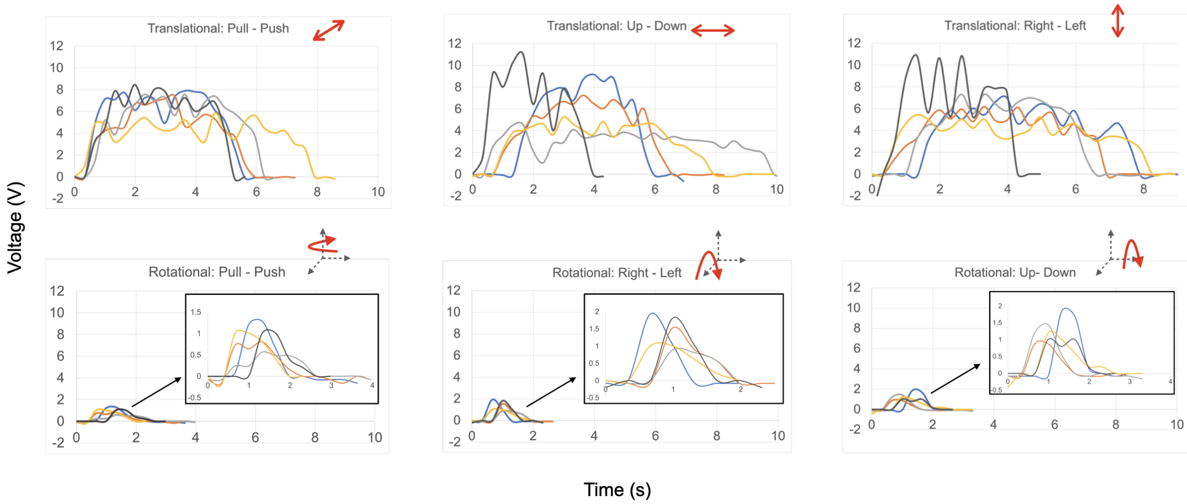


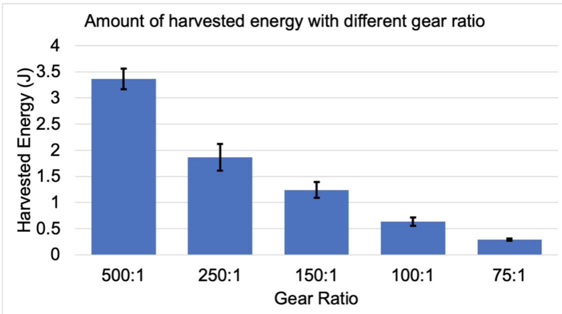
Fig. 2. Signal characteristics of interaction-powered motor mechanisms with two motion types: translational and rotational. Each color denotes data from one participant.

4.4 Resistance in Motor Powerline

Resistance in the motor powerline affects the output currents and thus the harvested energy. In practice, we found that increasing this resistance limits the output currents by motors and reduces the force and torque to actuate the mechanisms. This correspondence gives us a way of setting motor force/torque in a finer-grained manner using programmable resistors than using gearboxes, because gearboxes often have discrete gear ratios and are impossible to change by software. In this test, we connected the motor in series with a resistor. The device was configured to support translational motions and we used a gearbox of a 250:1 ratio. A capacitor of 2.5 F was connected to the motor-resistor setup for storing the harvested energy, which can be calculated by measuring the voltage increases using a multimeter. We gradually changed the amount of current generated by motors by changing the resistance (from 0 to 150 Ohm with a 25 Ohm interval). This change in induced current also changed forces needed to actuate the device, which we measured with the force gauge. Figure 3 right shows measurements of amounts of energy in response to the change of resistance. We found that the device was harder to actuate with a lower resistance value (in series) but can generate more energy. For example, a 100 Ohm resistor can reduce 54% of the total force required to move the device.

4.5 Harvest Energy from Real-World Objects

Previous tests outline the characteristics of interaction-powered harvested energy. To gauge more precisely how much energy can be harvested from users' interactions with everyday objects, we conducted tests on real



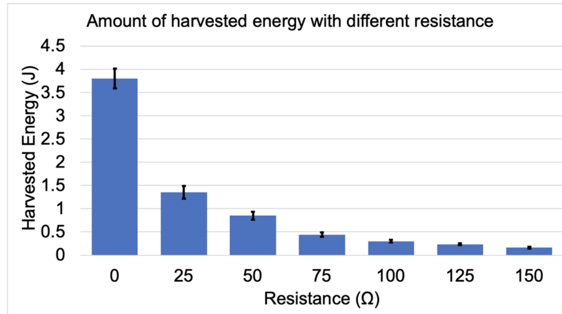


Fig. 3. Investigation of gear ratio's effect on harvested energy (left). Investigation of the effect on harvested energy from the resistance in the motor powerline (right).

everyday objects. We included 9 common objects, with 5 involving rotational motions (i.e., fridge door, CNC enclosure, window blinds, toilet lid, room door) and 4 involving translational motions (i.e., backdrop, drawer, trash can, dimmer switch). We designed 3D-printed gear mechanisms that turn both types of motions into motor revolutions (Figure 7). Details of these mechanisms will be discussed later in the paper (Section 5.2). We used the motor with a gear ratio of 250:1 in tandem with these mechanisms. An experimenter manually operated these objects and measured the harvested energy of each object in one trial. On average, each trial of manually operating these objects generated 0.56J (SD=0.32) energy. Figure 4 shows the voltage across a 100 Ohm resistor in series with the motors of these objects being manually operated in one direction. We omit the rest of the trial for them simply mirroring the signals shown around the 0V line. In general, these half trials took from around 1 to 14 seconds to complete. Objects with longer strokes (e.g., backdrop, window blinds) generated more power for inducing more revolutions of motors, than those with shorter strokes (e.g., dimmer switch, trash can).

4.6 Energy Consumed for Actuating Real-World Objects

Previous tests help us understand how much energy can be harvested from user interactions. Here, we investigate energy consumption in automatic operations – how much energy we need to actuate objects. With the same set of objects in the previous test, we used a DC power supply (DCV=4V) to power the motors, which induced sufficient torque to actuate these objects at normal speeds. We measured the current during the courses of object actuation in three trials.

On average, these objects consumed 2.77 J (SD=2.03) energy in one trial of their actuation (i.e., open and close). Similar to insights from the energy harvesting test, objects with longer strokes consumed more power for taking longer to complete the motion. Even on the same objects, actuation in different directions could consume different amounts of energy depending on if gravity contributes or resists the motion. For example, it takes 1.7 J on average to open a CNC enclosure door, while that number is 0.3 J for closing it. We also noticed that when the gear mechanisms were blocked by the objects from further movements at the completion of motion, motors were overloaded and drew a high current (i.e., stall current). This stall current measured approximately 120 mA with our motor, and consumed a lot of energy, for which we later designed our system so it can detect and cut off power timely to minimize energy wasted on unnecessary actuation.

5 MINIKERS SYSTEM

Based on insights from the aforementioned tests, and taking into account our design goals, we implemented *MiniKers* system. Our system is composed of: 1) a fully self-sustaining wireless circuit board, which connects

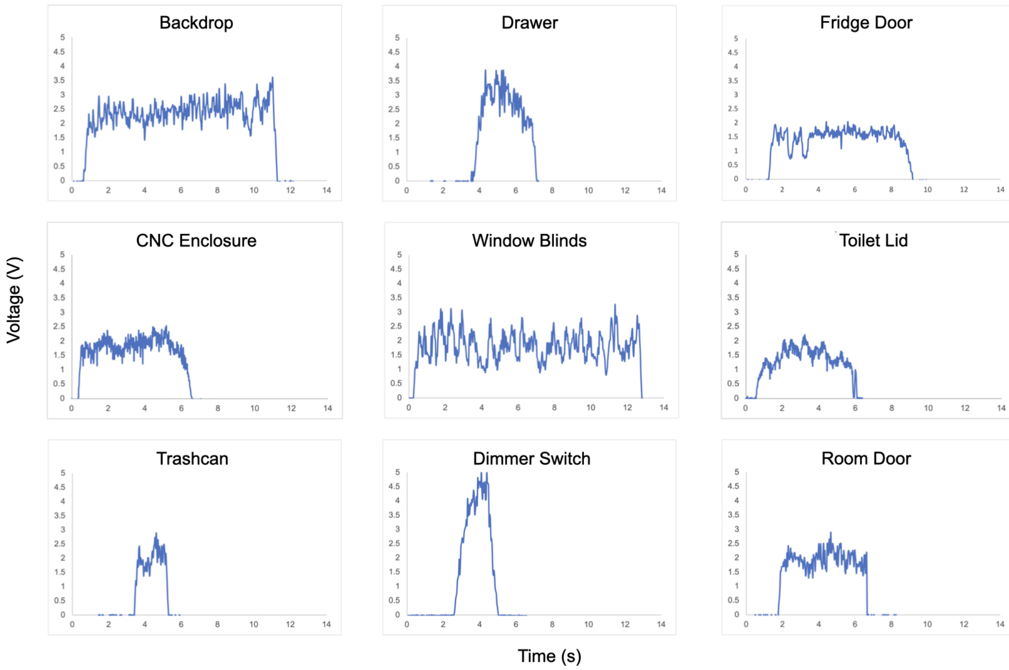


Fig. 4. Voltage-time plot of the 9 objects with gear mechanisms and motors (gear ratio = 250:1) attached. These objects were manually operated from one extreme position to the other (i.e., half trials).

to a mechanism and a motor to capture energy and actuate; 2) a phone application to support end users with a variety of interactions to activate the actuation, as well as to keep track of all *MiniKers* in the environment.

5.1 Hardware

Overall Structure: The *MiniKers* custom circuit (Figure 5) was designed to accommodate energy characteristics found in the previous investigation studies. The circuit has two energy storage devices: a rechargeable supercapacitor and a Lithium-ion Polymer (Li-Po) battery. We used a supercapacitor which has two capacitance options (0.6 F and 2.5 F) depending on the application – among the 9 objects in Figure 7, only the *MiniKers* for the backdrop used a supercapacitor of 2.5 F capacitance for the significantly large amount of energy generated in each manual operation. Similar in concept to the power grid stability support for renewable sources, supercapacitors and Li-Po batteries (3.7V, 70mAh) provide stable energy storage to buffer the intermittent user-interaction energy. The Li-Po batteries can power the motor continuously for more than two hours. This deep energy reservoir makes the system more tolerant to short energy consumption surge, improving the overall system's power reliability.

The circuit features a discharging and a charging mode to support the motor being used as either an actuator or a generator. Figure 6 shows the power architecture of *MiniKers* which accommodates the coexistence of these two modes on the motor front end. In the discharging mode, the motor is driven by a motor driver, drawing power from the battery. A MOSFET is used to disconnect the charging line in this mode. In the charging mode, the motor is driven by user interactions and generates currents, which are regulated by a bridge rectifier and immediately stored in a supercapacitor. Once the voltage of the supercapacitor reaches a certain threshold, the boost converter starts working and feeding energy into the battery.

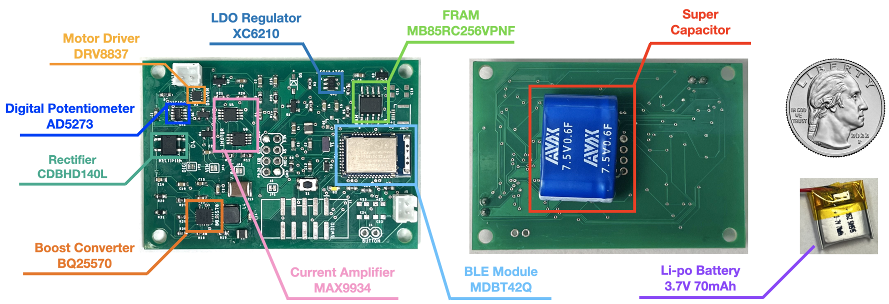


Fig. 5. *MiniKers* circuit board (front and back).

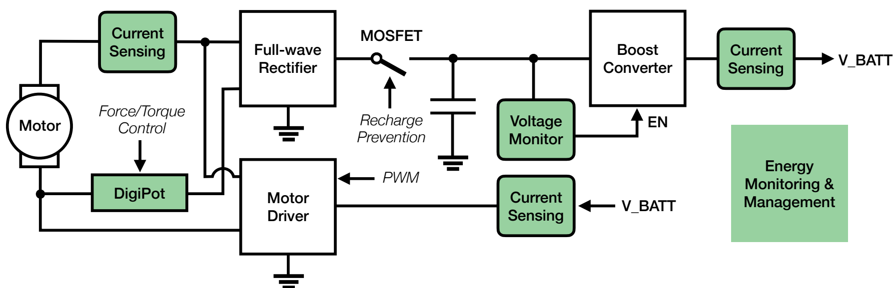


Fig. 6. The power architecture of *MiniKers*.

In addition, our circuit features an FRAM to store energy-related information (i.e., the voltage of the battery, energy charged into the battery, and energy consumed by the motor and the rest of the circuit) and time-related information (i.e., timestamps of charging, events of manual and automatic operations). We used a digital potentiometer (DigiPot) in the motor powerline to adjust forces/torques required in users' manual operations of objects. This DigiPot was disabled in automatic operations. In total, our board costs $45 to make as a one-off prototype and could be even cheaper in bulk productions.

Energy-Efficient Implementation: We optimize the energy efficiency of our system on two fronts: lowering power consumption and increasing harvested energy.

Our boards use a Nordic nRF52832 SoC packaged with Raytac's MDBT42Q BLE module, which features ultra-low idle-mode power consumption (less than 2 μA [45]). We implemented two standby modes depending on if BLE connectivity is required. The BLE connectivity allows *MiniKers* to hitchhike existing interactions on smartphones using our phone apps. When users are expected to control *MiniKers* with smartphone interactions, BLE connectivity should be readily available and thus our system should maintain a periodical BLE advertising (i.e., first standby mode). To reduce power consumption, we tuned advertising parameters, including TX power (0 dBm), advertising interval (318 ms), and period (5 s). We also implemented a second standby mode which does not require BLE connectivity but uses event triggers on GPIOs (i.e., hardware interrupt) that monitor physical interactors such as buttons. We will describe the phone apps and interactions our system supports later in the paper (Section 5.4).

Other than the SoC, the rest of components are also low-power to minimize the current draw of the whole circuit (e.g., motor driver: Iq=30 nA, boost converter: Iq=5 nA). We also configured GPIO pins to be in high-impedance mode when they are idle. To further reduce power consumption, we used power gates by adding multiple high-side p-channel MOSFET as power switches to shut off major components including current amplifiers, FRAM, and DigiPot when they are not in use.

Additionally, we configured a GPIO to capture hardware interrupts triggered by the motor in the generator mode (i.e., actuated by user interactions) to turn on high-speed ADC (at 10 FPS). This allows us to preserve the sensing resolution without losing much energy on ADC in the standby mode when no user interaction happens.

We also found large stall currents that occur at the ends of object motions (e.g., drawer fully closed/opened) when the motor is stuck. To shorten durations of the stall current to preserve energy, we implemented stall current detection using thresholding (i.e., stall current is often significantly larger than ordinary motor driving current) and cut off power to the motor immediately once the stall current is detected.

Finally, we implemented features to increase the efficiency of energy harvesting. We used a low-forward-voltage rectifier, the output of which goes immediately to a supercapacitor (i.e., the storage capacitor), which has high pulse power capability, capturing as much energy as possible from the motor. Our system turns on the boost converter only when the voltage across the storage capacitor exceeds 2 V, forcing the boost converter to operate in the *boost mode* which has the highest converting efficiency.

Energy as Sensory Feed: Our system monitors the harvested and consumed energy which can serve as sensory feeds needed in smart environment applications. Two current amplifiers are leveraged to sense bi-directional currents through the motor and battery. The voltage level of the supercapacitor and battery are measured with analog pins on the SoC. By monitoring the energy flow, *MiniKers* keep track of the battery level and adapt the resistance in the motor powerline to keep them self-sustaining. Specifically, our system could increase the harvested energy per manual operation by decreasing the resistance of the DigiPot. If self-sustaining is not feasible (i.e., there are more automatic operations than what the energy harvested from manual operations can sustain), *MiniKers*' energy monitoring capability could be used to request user intervention (e.g., charge/exchange batteries, add other types of harvesters) as opposed to doing nothing and letting the battery drain out, which could result in unexpected failures that lead to costly errors.

Without having to use external sensors to probe user and environmental context, our system can yield quite significant amount of information by observing the energy pattern. For example, rich information can be inferred by sensing the magnitude and direction of the motor-induced current, which correlates with the motor status. For example, the current direction of the motor on a door *MiniKers* indicates whether the door is being closed or opened. We will show more sensing modalities in section 6.

5.2 Gear Mechanisms

We designed 9 two-gear mechanisms with unique variations to adapt to objects across a multitude of environments. These mechanisms provide additional gear ratios to facilitate our motors to actuate objects. We designed these mechanisms to function in a bi-directional manner in the sense that input and output gears could alter their roles according to the two different modes of system operation (i.e., manual and automatic). We used an Ultimaker S5 3D printer to print these gear mechanisms with PLA of 100% infills. We resolved the following challenges by fine-tuning the mechanical parameters (i.e., module, gear ratio, pivot axis, material infill, and locations relative to the host objects) of the gear:

- The additional force caused by the gear mechanisms in concert with the motors should not be too large for a user to manually operate objects.
- Sufficient force could be provided to actuate objects (many of which could be heavy) when these mechanisms are put in a reverse configuration.

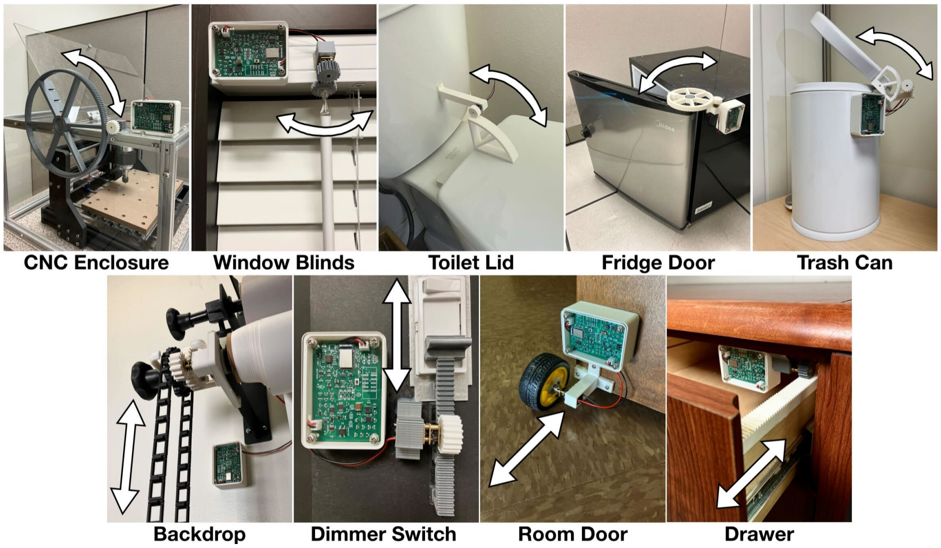


Fig. 7. *MiniKers* instrumented on 9 everyday objects, enabling self-sustaining automatic operations. Top row shows objects with rotational movements and bottom row with translational movements.

- For objects with translational motions (e.g., drawers), the mounting height of the pinion with respect to the rack has to be precisely adjusted to avoid additional force/torque due to friction while maintaining robust couplings between the two.
- For objects with rotational motions (e.g., toilet lid), the mechanisms have to be precisely mounted on the axes, or the gears would either jam or lose contact.

5.3 Phone App

To facilitate the use of *MiniKers*, we implemented two phone apps: one that allows users to control devices (the "control app"), and one that allows building maintenance and facility to review historical usage data (the "management app"). The control app displays the BLE devices that are in range, filtering out non-*MiniKers* devices using custom UUIDs. It allows users to connect to *MiniKers* and control them remotely with interactions available on the phone. Besides touch interactions, the control app also supports voice commands. To start, the user presses a button, then speaks a command, such as “open door”. Upon each connection with *MiniKers*, both the control app and the management app retrieve unread data from the device FRAM. This data includes key timestamps of events, battery voltages, motor-related currents, and actuation type (automatic or manual). It is then stored in an SQLite database and uploaded to the app-specific folder under the user’s Dropbox account as a proof-of-concept implementation of cloud storage.

The management app downloads the database from the server during launches and allows users to select a device to view its historical data. After selecting a device in the management app, the user is taken to a calendar view, which displays colored dots on each date to indicate automatic and manual usage with orange denoting automatic operations and green manual operations. This allows users to observe general usage trends at a glance, e.g., on which days a device was used and roughly how often automatic operations occurred compared to manual ones. From the calendar page, the user can tap on a day to view its detailed data.

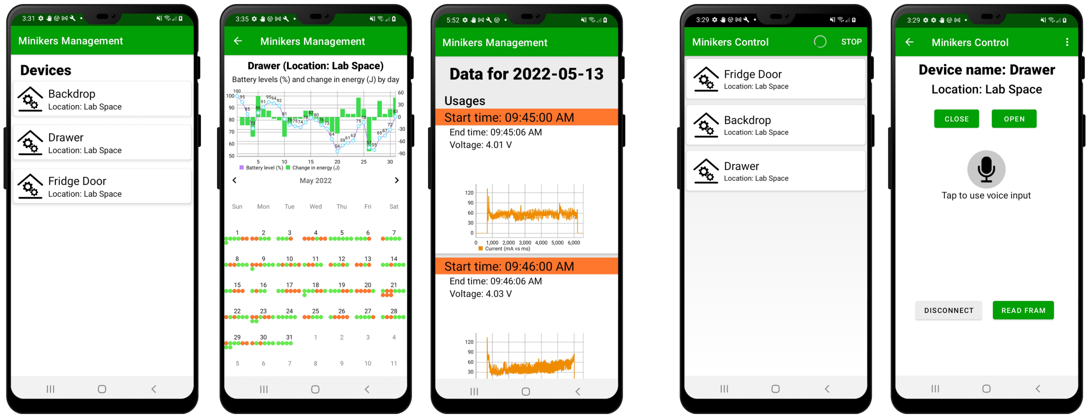


Fig. 8. Left: the data management app (homepage, calendar view, and single day data display); Right: the control app (Bluetooth scan and control).

5.4 Interaction Modalities

MiniKers support multiple interaction modalities to accommodate for various interactions affordable in user environments. First, our systems lead out several external analogs and digital pins that could be quickly turned into touch sensing mechanisms using **mechanical controls** (e.g., click, pan, twist, tilt [69]) or **capacitive touch** which features thin conductive layers resulting in minimal intrusiveness to existing objects (e.g., [54]). Second, these spared pins and interface bus (i.e., SPI and I2C) we led out can interface *MiniKers* with **external sensors** such as proximity, motion/occupancy, gesture, pressure, heat, humidity, CO2, vibration/acoustics sensors, for additional sensing capabilities. Additionally, our phone apps extend the interaction modality of *MiniKers*. Users could use **touchscreen interactions** to control *MiniKers*. We also implemented **voice control**, a commonly used interaction modality to assist users with limited upper extremity mobility [49]. Finally, *MiniKers* support **assisted actuation**, with which our system senses initiations of user manual operations of objects and actuates these objects to complete the rest of the operations, a common feature on automatic doors.

6 VALIDATION

We validated *MiniKers* with a series of micro-benchmark tests described here. Results from these tests outline our system's performance envelope such as power consumption, motor actuation, and harvesting efficiency. Not only do these results further our understanding of *MiniKers*, they also provide benchmarks for future systems in similar application domains to compare with and improve upon, providing a foothold for ubiquitous self-sustaining smart environment automation research. Results in this section are validated by a deployment study which we will discuss in Section 7.

6.1 Power Consumption

Intuitively, our system consumes different amounts of power when operating under different modes for differences in power to motors, frequency of ADC, and BLE communication. We used Nordic PowerProfiler II to profile the current draw from battery of *MiniKers* over time in energy harvesting mode (i.e., manual operations) and actuating mode (i.e., automatic operations). Figure 9 shows the results, with key states highlighted. Table 1 shows power consumption of main components. In the standby mode, *MiniKers* draw 45 µA from the battery. Of note that the power consumption for the standby mode runs 1) operation of the SoC and its supporting components

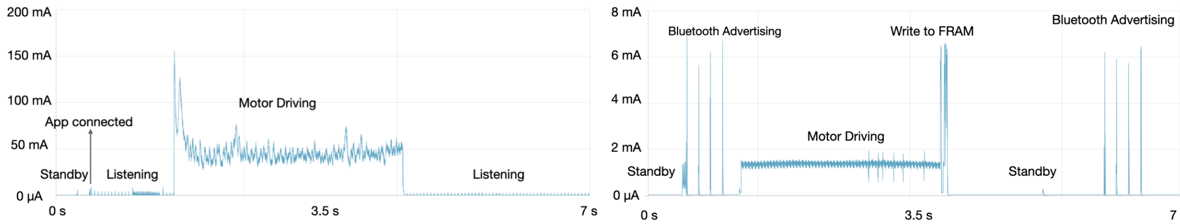


Fig. 9. Current draw of *MiniKers* during a typical automatic (left) and manual (right) operation.

(e.g., regulator), and 2) periodic BLE advertising. A manual operation does not involve BLE communication and has a power consumption that runs 1) ADC (hardware interrupts by motor revolutions due to user interactions), 2) boost conversion, 3) writes to FRAM, 4) current measurement, in addition to 5) the SoC operation. The automatic operation consumes power for 1) powering the motor driver that drives the motor, 2) BLE communication with the phone app, 3) writing to FRAM, 4) current measurement, as well as 5) the SoC operation. We found an average power consumption of 26.6 mJ per transmission of one Kilobyte through BLE with our system. Of note that the power consumption of enabling the activation of automation (i.e., accommodating the aforementioned user interactions) is negligible for touchscreen interactions and voice control hitchhiking existing BLE communications, and other interaction modalities (e.g., mechanical controls, assisted actuation) implemented with hardware interrupt. Accommodating interactions based on external sensors and capacitive touch could consume more power but both can be implemented in a low-power manner by careful part and frequency/duty-cycle selections.

Table 1. A breakdown of power consumed by major components (ones labeled PG are power gated). Measurements were collected when power gates were switched on and when these components are enabled.

Component (part number)	**Power (µW)**
Motor driver (DRV8837)	1584.6
Current amplifier (MAX9934)	2416.8 (PG)
SoC Mininum System	148.5
FRAM (MB85RC256VPNF)	33 (PG)
DigiPot (AD5273)	3.66 (PG)
Boost converter (BQ25570)	3.8

6.2 Energy as Sensory Feed

The mere presence of energy can often serve as sufficient sensory feed. In fact, repurposing energy as sensory feeds has been shown in several previous works [8, 16, 73]. In the context of this research, for example, there will have to be generated energy when a door panel is in motion, and thus sensing the presence of the generated energy can reveal uses of the door. Even better, motor mechanisms yield currents that constitute the energy flow, revealing richer signals of motions – e.g., speed, duration, and direction. And thus by sensing harvested energy through sensing currents, we can infer much about user environments without external sensors.

We used *MiniKers* system's current sensing to measure current outputs by several objects and compare them with the Nordic Power Profiler II. Figure 10 shows the results which indicate a modest difference between these two sets of measurements though the noise floor of our built-in current sensing is higher. We used a room door as an example to demonstrate the sensing ability of *MiniKers* (Figure 11). We used our built-in current sensing

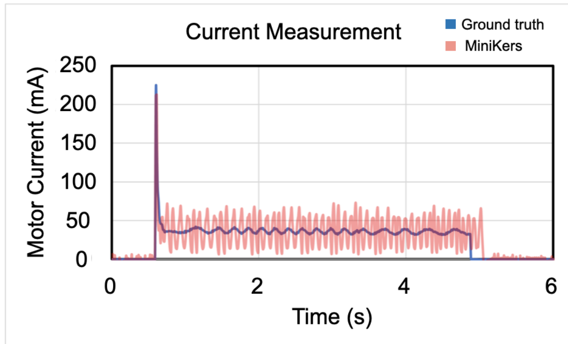


Fig. 10. Comparison of current measurements with *MiniKers* and Nordic Power Profiler II (ground truth).

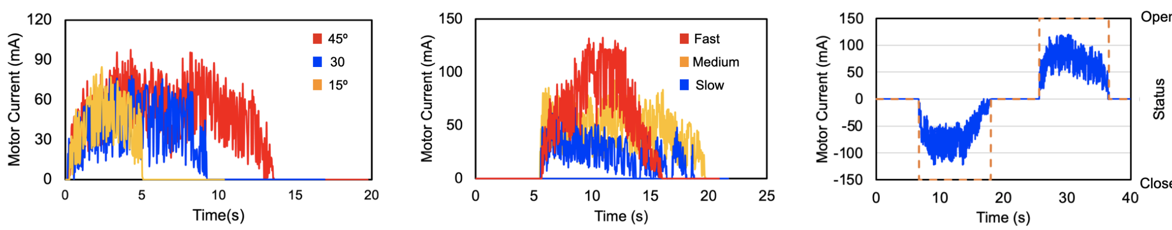


Fig. 11. Example of using *MiniKers*'s sensing capability. Left: The integral of motor current correlates door angle. Center: The speed of opening/closing the door can be inferred from the magnitude of current. Right: The direction of the current indicates the door status.

to measure current outputs by objects in their manual operations. Uses of doors indicate utilization rates of environments, and the states of doors often have social meanings – an opened door vs. a closed door. Rich sensing is needed and has been researched in prior work [57, 70, 72, 73], and there have been commercialization efforts focusing on door sensing [5, 44]. In the context of room doors, our system detects what angle does the door open to (Figure 11 left); at what speed (Figure 11 middle); and in which direction (Figure 11 right), all of which are achieved through repurposing the motor as a sensor and leveraging the harvested energy as sensory feed.

7 DEPLOYMENT STUDY

7.1 Procedure

We deployed 9 *MiniKers* across 3 locations: a lab space, an office, and an apartment, each featuring common but different functions (Figure 12). These locations were occupied during the deployment and *MiniKers* were exposed to users and elements expected to be seen in everyday settings (e.g., humidity, pressure, impact, user interactions). Each *MiniKers* was deployed for 48 hours during which one experimenter visited these devices three times a day (i.e., morning, noon, and evening) for performing trials that were recorded for ground-truth data. Specifically, during each visit, the experimenter performed 25 manual trials of the object consecutively with a five-second interval in between, followed by 3 automatic trials using the phone app (i.e., the control app). In manual operations, the experimenter manually actuated the object from one extreme position to the other

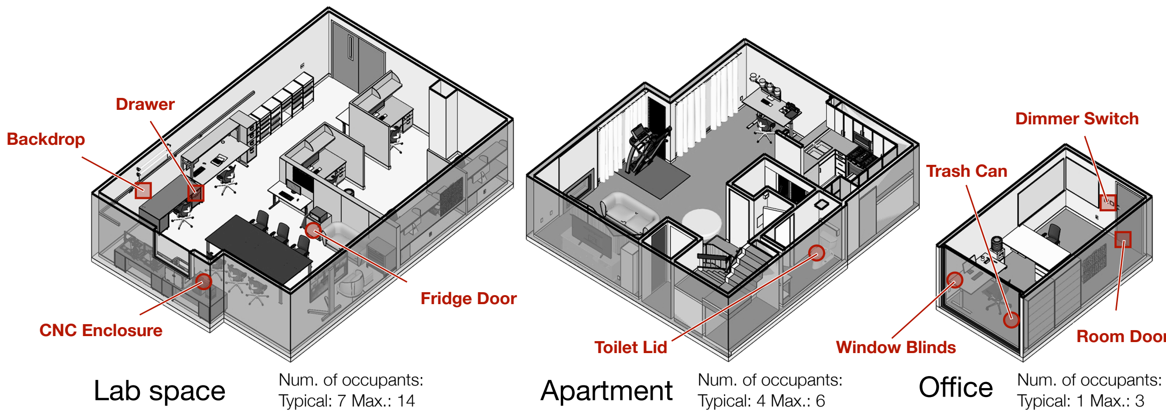


Fig. 12. *MiniKers* were deployed at 3 locations on 9 objects. 3D models of these 3 locations with details of their configurations are shown. Objects with translational motions and rotational motions are denoted with squares and circles respectively.

(e.g., blind blades tilted at 0° for minimal light through, and at 90° for maximum light through). We collected the *MiniKers* boards at the end of the deployment and parsed the data in the FRAM for analysis.

7.2 Results

Across the 3 locations and the 9 *MiniKers* devices, the averaged energy harvested from each manual operation was 0.26 J (SD=0.37) and the energy spent in each automatic operation was 4.46 J (SD=4.47), resulting in approximately a 24:1 ratio. In other words, there need to be around 24 manual operations of objects before *MiniKers* gather sufficient energy for one automatic operation. This is a rough estimation omitting several supporting functionalities (e.g., communication and system standby) that also consume power, as we have shown and quantified in the technical validation (i.e., Section 6). For this reason, the 24:1 ratio of manual to auto operations is the upper bound of performance if *MiniKers* are to be deployed for real-world applications. Nonetheless, this ratio gives us an estimate, which is important in setting up user expectations and could guide users in their deployments of *MiniKers* in the real world. Below we break down this result into details with an in-depth analysis.

Figure 13 shows an example of fridge door events over time during the deployment. Table 2 shows harvested and consumed energy per manual and automatic operation for each object. First, we confirmed the observation from our validation test that more energy can be harvested from objects with longer motion strokes (either translational or rotational). Heavier objects (e.g., room door, toilet lid) consumed more power to actuate. In general, objects that drew more power for actuation generated more power in their manual operations. Despite this correlation between the amounts of consumed and harvested energy, the manual-to-auto ratio still varied a lot across different objects, possible reasons for which could be differences in objects' original structures. For instance, some objects like the toilet lid have higher frictions to be actuated due to the anti-slam mechanism than others. There is also variation introduced by our gear mechanisms that could contribute to the variation of the manual-to-auto ratio.

Finally, with our board's current sensing capability, we can readily measure energy efficiency by measuring and comparing the energy generated by the motor and charged into the battery. The efficiency is computed as a ratio between the two. We estimate the energy generated by the motor by monitoring the voltage increase on the supercapacitor. Energy dissipated on the rectifier and DigiPot is relatively small and thus neglected in this calculation. On average, we found an energy efficiency of 57% (SD=18). Table 2 shows a breakdown of this

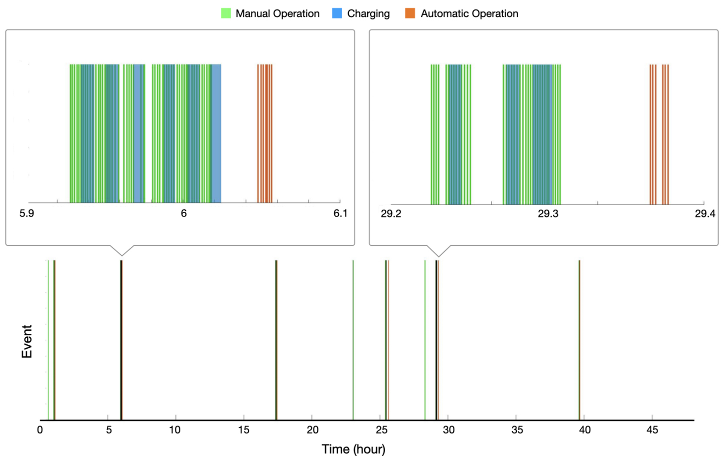


Fig. 13. Event distribution over time of the *Fridge Door* during the deployment study. There are six periods of time in which events are concentrated due to trials performed by the experimenter. Figures on the top show two zoom-in views of these recorded events. Isolated events are due to the daily uses by owners of the space.

Table 2. Average energy harvested and consumed per manual and automatic operation by the 9 objects.

Object	Harvested Energy per Manual Operation (J)	Consumed Energy per Automatic Operation (J)	Manual-to-Auto Ratio	Energy Efficiency
Room Door	0.26	10.34	40	65%
Trash Can	0.06	1.01	17	57%
Window Blinds	0.09	2.60	28	34%
Dimmer Switch	0.03	0.40	14	45%
Drawer	0.31	2.03	7	68%
Backdrop	1.22	13.32	11	81%
CNC Enclosure	0.18	1.98	11	80%
Fridge Door	0.07	3.03	43	37%
Toilet Lid	0.12	5.41	45	48%
Average (SD)	**0.26 (0.37)**	**4.46 (4.47)**	**24 (15)**	**57% (18)**

efficiency across all objects. Like the manual-to-auto ratio, this energy efficiency also varied by object for the same reasons as previously mentioned.

8 DISCUSSION

8.1 Ultra-Low-Power Standby Mode

We found a non-negligible amount of energy consumed by *MiniKers* in their standby mode during the deployment study. This energy outlet is going to be even more significant in longer-term deployments (e.g., year-round). This power consumption can be lowered (i.e., from 148.5 to 108.9 μW) if controls are not mediated through BLE connectivity but with physical interactors (e.g., buttons), which are common to find on existing automatic devices

– automatic doors in most commercial buildings would simply use a button as a tangible and readily available interactor for control. It is also possible to choose microcontrollers with lower power consumption for e.g., the TI MSP430 series, which have shown promise in many previous energy-constrained computing systems.

8.2 Gear Mechanism Installation

Installing gear mechanisms onto objects with rotational motions (e.g., fridge door, toilet lid) poses a real challenge. These mechanisms must be precisely mounted on the object's axis of rotation, or the *MiniKers* gear transmission will either jam (gears being too tight that creates unnecessary friction making them hard to actuate and easy to wear) or lose contact (gears being too lose that creates backlash, skipping teeth during its rotation). This rotation axis is intrinsic to objects once they are manufactured. Thus, pinpointing their axes of rotations can only rely on a trial and error approach and could be laborious. Additionally, some objects might not be properly leveled against their surroundings and require further adjustments to our mechanical design.

8.3 Cope with Intermittency

The current implementation of *MiniKers* does not provide mechanisms for recovering computational state after a power failure. Significant work has been done in the area of "intermittent computing" [21] where energy harvesting and battery-free devices will frequently die when energy is not available, then reboot and restore the previous computational state: examples include the Battery-free Game Boy [15] which allowed for power failures without changing game state. Using the small Li-Po battery as a rechargeable energy reservoir improves power stability for our design and allows us to explore the ideas around these user-powered items without the added complexities of intermittency. However, future work could pursue full-stack implementations of intermittent computing to enable a much longer lifetime and battery-free, perpetual operation of *MiniKers* in more real-world use scenarios.

8.4 Usability and User Behavior

MiniKers were deployed in common everyday environments in which occupants used the instrumented objects as they normally would during the development. The system worked well with only a few breaking parts which could be improved with superior fabrication techniques (e.g., metal printing) and more permanent attachments (e.g., screws). We didn't notice any difficulties of using these objects in manual or automatic operations except for minor issues such as slow actuating speed, and long Bluetooth scanning time. Though falling out of the scope of our core research contribution, the lack of a systematic usability study is one of the limitations of this project. The usability of *MiniKers* should be properly investigated in our future work, including studies on populations with different motor capabilities, frequency of uses in different environments and applications, and beyond. This investigation will further our understanding of user behavior in response to enhancements of their environments with automation. Having an option of automatic operation might alter people's behavior when for e.g., automatic operations are considered more sanitary and thus preferable than manual operations that require contact. Furthermore, future research will investigate how to improve users' awareness of energy using for e.g., ambient displays that communicate to users the availability of automatic operations and alert facility when systems need interventions after recognizing that self-sustaining is impossible (e.g., the demand for automatic operations is too high).

8.5 Long-Term Deployment

While results from this work show promise, we are cautious that long-term deployments might reveal insights beyond the scope of this work but are still valuable for improving the practicality of our proposed people-as-power technique in the real world. To fully investigate this, we plan to deploy *MiniKers* for longer terms at our campus (i.e., year-round) and look for opportunities to collaborate with owners of public spaces such as shops, grocery stores, and restaurants for deployments in spaces of a wider spectrum of uses.

8.6 Intrusiveness

Though we did not optimize *MiniKers* for size, it is possible to use superior fabrication techniques to have gear mechanisms with smaller sizes while maintaining the same gear ratios. Smaller gear mechanisms require finer teeth and therefore stronger materials, which can be achieved with metallic materials using casting, milling, or DMLS 3D printing. It is also possible to use motors with higher torques and thus can drive objects without external gear mechanisms. This correspondingly requires better driving capabilities from our circuit, which we plan to investigate in the future.

8.7 Multiple Energy Sources

Though we center *MiniKers* around the concept of people-as-power with the sole energy source being user interactions, it is possible and should be even more practical, to utilize multiple energy sources in the real world. For example, solar cells, triboelectric nanogenerators, piezo, and Peltier junctions can be added to *MiniKers* as secondary energy sources.

8.8 Open Source

We believe *MiniKers* system is an effective platform and evaluation vessel that opens opportunities for turning user interactions into power sources for research in ubiquitous computing, IoT, and cyber-physical systems. To facilitate researchers building on top of this work, joining forces on creating interaction-powered automation systems, and further developing the design concept of people-as-power. We will open source this research (i.e., PCB, firmware, software, 3D design files) at https://github.com/hilab-open-source/minikers.

9 CONCLUSION

We present *MiniKers*, an fleet of interaction-powered environment automation devices that harnesses energy from user interactions, achieving self-sustaining automatic operations that could last for long periods of time without human intervention (e.g., exchanging batteries). By leveraging our key observation that user motor capabilities in the environments are often heterogeneous, *MiniKers* repurpose the very motors for actuating objects as generators to harvest energy from their manual operations. We developed a custom circuit that features power management, programmable motor powerline resistance, PWM motor drive, event-triggered sensing and computation, nonvolatile memory, and BLE communication. We also developed two phone apps, one for interactive control and the other for data management. A series of technical validations and a 48-hour deployment study were conducted to prove the efficacy of our system.

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