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Implementation of Input Functionality Using Energy Source for Further Miniaturization of Small Devices

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Abstract: Miniaturization is one of the keys to realizing ubiquitous and wearable devices with greatly improved practicality. The barriers to further miniaturization include energy sources and the systems for user input/output. Completely removing direct physical interaction with the user and conducting all interaction through intermediary devices is an easy approach to further device miniaturization. Direct interaction, however, provides an alternative, redundant, and sometimes quite intuitive means of device control, and so study of its implementation is warranted. This paper explores how to integrate energy supplies with input systems while ensuring miniaturization. The proposed technique detects the deliberately sequenced interruption of the energy supply, forced by the user, as a command. It is implemented on prototypes with a battery and a PV (photovoltaic) module, and finally, applied to active tags as a typical example. The technique is practical and promising for further device miniaturization.

Keywords: miniaturization, ubiquitous/wearable device, energy source, input functionality

1. Introduction

Small devices with high functionality can now be prototyped and manufactured given the exponential enhancements seen in various fields, such as semiconductor manufacturing and wireless communication technologies. Device miniaturization not only helps the user to carry them everywhere, but also has the potential to change our computing environment in everyday life. While the traditional computer now includes smartphones, it is becoming possible to interact with an extremely wide variety of devices, some of which are embedded in the environment while others travel with us. This trend is seen most clearly in the IoT (internet of things) [2] and the popularization of wearable devices. It can be also regarded as an introduction to ubiquitous computing [36], tangible bits [13], and wearable computing [21].

From the viewpoint of hardware, a standard device consists of an energy source, electric circuits, and input/output systems. The energy source supplies electric power to drive the device and the circuit implements the functions of the device. The input/output systems are hardware that provide means to communicate with external devices and/or the user, such as wireless communication modules, connectors for wired connection, mechanical switches, LED indicators, and displays. Most devices offer several input/output systems, for example, both a wireless module and a power switch. The dominant trend, miniaturize the device to encourage penetration in everyday life, is hindered by the energy source and input/output systems; electric circuit miniaturization is far more successful. The performance of the energy source depends on

its physical size, and thus decreasing its size reduces the running time of the device or limits the conditions under which the device works well. Physical device size is limited to the level at which user control remains practical. The input/output systems that directly interact with the user, e.g., switches and displays, cannot be miniaturized beyond practical limits. When a larger intermediary device, such as a remote controller or smartphone, bridges the small device and the user, usability is improved as the user interacts with the intermediary device and the temptation is to strip the input/output systems from the small device entirely. For example, TVs are often controlled indirectly via remote controllers and the user pushes the obscure and cryptic buttons on the TV only when the remote controller goes missing. This redundancy, buttons on the TV itself, increases device size and cost, but many large devices, especially home electronics such as TVs and air conditioners, often provide such redundancy to create a sense of reassurance.

The expectation is that enormous numbers of small devices will be scattered throughout the environment in the future, most of which will be controlled by a few common intermediary devices unlike large devices. For example, devices of a sensor network have almost no need to directly interact with the user so the use of a common controller is suitable. Although there are several benefits to such a configuration, we believe that small devices must retain input/output systems for directly interacting with the user even if the devices seldom require direct interaction. The importance of direct interaction will increase with the number of small devices around us. For example, direct interaction will help the user to select and control just the device desired. When only indirect interaction is available, the user must identify the device desired from among the many device candidates offered by the intermediary devices. The difficulty of this will only increase with

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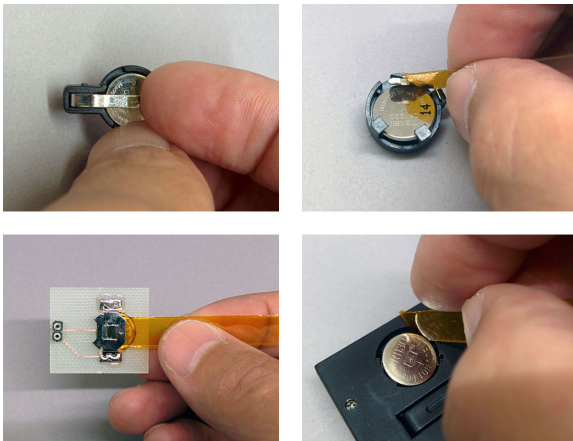a)   manabehiroyuki@acm.org
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Fig. 1 Examples of blocking actions using battery holders. When the electrode is slightly shifted by the finger or nail, the energy supply is interrupted (top left figure). It is the simplest action and suitable for relatively large battery holders. Sliding a thin isolating sheet into the contact between the electrode and the energy supply is blocked (other three figures). It works with various battery holders and the fingers will be protected from being hurt.

Fig. 2 A PV module (left figure) and examples of blocking actions using PV modules. When several fingers or the palm approaches and covers the whole PV module, the illumination level falls enough to be detected as interruption of energy supply (middle figure). Many objects are opaque and can replace the fingers or palm. Considering partial shadowing, finger-touch on one PV cell also decreases energy generation and is detected as energy blocking (right figure).

the number of distributed devices. Moreover, direct interaction is required when the user checks whether the device works properly and powers up the device.

Of course, not all interactions need be performed via direct interaction, only the most basic tasks. Most current devices have hard power switches that afford direct interaction and those that lack power switches are few, such as cheap toys and emergency flashlights. Hard power switches will disappear to meet the demands for cost reduction, form factor enhancement, and reliability as extremely low power techniques are maturing and OFF state will be replaced by sleep. This paper reports a technique to add input functionality assuming such a future. There are several techniques that can be realized direct interaction for small devices, and some of them place no limits on miniaturization. For applying the techniques to practical devices, not only miniaturization but also other attributes such as power consumption and cost have to be taken into consideration. The technique described in this paper integrates an energy source and input systems for further miniaturization while preserving direct interaction. Examples are shown in **Figs. 1** and **2**. The user interrupts the energy supply by manipulating the battery holders or shadowing the PV modules, and the device detects the interruptions and recognizes sequences of interruptions as commands. Since the energy sources are also used as a means for direct interaction, additional switches and sensors are not required, which would otherwise increase the size, power consumption, and cost. Though the proposed technique requires some additional circuits to detect the energy interruptions, it only slightly increases the size, power consumption, and cost and so is a practical solution to implement a means of directly interacting with small devices.

2. Related Work

We posit that the major barrier to device miniaturization is how to implement input functionality without increasing device size. A lot of work has already attempted to embed input functionality into small devices, for example [10], [22]. Most small devices on the market, such as smart watches, use touch displays or touchpads as they have relatively low power consumption and provide rich interaction functions. It is known that small touch displays suffer from the occlusion issue, sometimes called the fat finger problem; the finger hides the contents of the display and is error prone. NanoTouch places a touchpad on the device's backside to resolve this issue [4]. Touch sensors implemented along the device's sides can detect grasping motions as the user's input [7]. A single touch sensor that detects several states of touch and grasp [31] or multi-touch gestures [19], will decrease implementation cost and increase expressiveness. While touch displays and touchpads are interesting, they limit the physical area for touch interaction and make further miniaturization more difficult since touch interaction is performed on just the device.

There are techniques that expand the interaction area to beyond the device; camera-based approaches are traditional, such as Refs. [14], [23], [35]. This expansion removes the limitation and well suits for quite tiny devices. Audio and vibration travel some distance, thus microphones can also expand the area, such as Refs. [11], [12]. An accelerometer is an attractive tool for detecting gestures regardless of device size [8], [16]. Various sensors including magnets and magnetic sensors [6], [9], photoreflectors [5], [25], distance sensors [15], and optical sensors for computer mice [10] can be used to detect user's input performed outside the device. However, all these require some kind of independent sensor just for input functionality, which increases cost and power consumption. Some techniques reuse the signals needed to implement the main functionality of the device. For example, the GSM (global system for mobile communications) signals of a cellular phone can be used to detect gestures performed around the phone [37] and input functionality can be added to unmodified headphones [17].

As described before, the barrier to further miniaturization includes both energy sources and input/output systems. First, we consider miniaturization from the viewpoint of the energy source. Technologies related to energy consumption directly impact the running time, efficiency, available environment, and device dependability. While work continues to improve the energy density and efficiency of power generation and consumption, many studies have also addressed energy from the HCI (human computer interaction) field. A typical research topic is feedback based on energy [28], such as the investigation of user's charging behavior [29] and an electrical extension strip that indicates the levels of electricity passing through it [3]. Human-powered devices that use input systems as energy sources are another topic. For

example, pushing a switch or walking can generate energy to drive the device [26] and rotary action is also a possible alternative [33]. While these studies focus on the energy generated by the user's actions, the proposed technique targets energy interruption. When the device does not include its own energy source and energy is supplied from outside, power line communication (PLC) can be used to merge power and data/control channels. While PLC is often applied to the AC power feeds of home appliances, it can be implemented on DC power feeds [34] as well as PV modules [30]. They can transmit much power and suit home appliances. There are two dimensional sheets that can transmit both power and data [1], [32]; most PLCs use one dimensional power cables. These two dimensional PLC techniques allow free device placement within the sheet. Such configurations are effective, for example, when all devices are on a table top or the user's shirt. CoBIT that receives both data and energy via IR [24] and passive RFIDs are also a kind of PLC. The user can easily control the dimming functionality of the light without modifying the building by replacing the light itself with one that recognizes commands performed by quickly turning the simple wall switch OFF to ON, which is also a type of PLC. Examples in which a single switch is used to input commands are found everywhere, e.g., switches on headphone cables to control audio players and power switches that are assigned different commands according press duration.

3. Proposed Technique

The proposed technique uses the energy source as an input system for further miniaturization. The basic idea is that the device detects the voltage drop or drops caused by user's intentional blocking of energy to the device, and the sequence of the drops is recognized as a command. There is no need to embed additional sensors, it is easily implemented, and incurs little additional power consumption. It aims to provide only basic interaction with the user. Since most current devices have power switches that offer direct interaction, the proposed technique may seem unnecessary. The idea is easily implemented even when such a switch is present, and increases control expressiveness. The implementation described in this paper assumes that switches will be eliminated for further miniaturization, lower cost, and enhanced robustness.

The idea is not so novel and is a type of PLC in the broadest sense. The differences from regular PLC are that the energy source is inside the device, the data signal directly indicates the user's action, the bit rate is low, one-on-one communication is enabled, and only a small and low power consumption circuit without coupling/decoupling circuits is needed. These are suitable for small, ubiquitous, and self-sustaining devices and as a means of realizing minimal direct interaction with such devices. For example, when the energy source is separated from the device like regular PLCs, the costly routing of power cables to all devices is unavoidable and it is difficult to distribute large numbers of devices. Two dimensional PLC techniques do not support the devices outside the sheet. Moreover, they do not provide a means for directly interacting with the device. The proposed technique allows installation ubiquity and direct interaction. While the idea is
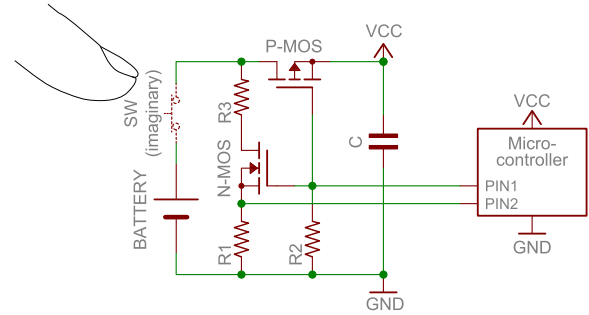

Fig. 3 Example of a circuit to detect energy supply interruption from a battery. The micro-controller periodically monitors whether the energy supply is blocked. PIN1 is set HIGH while monitoring. PIN2 as input becomes LOW when the battery is not connected and vice versa. While not monitoring, PIN1 is set LOW, so there is no energy loss. Note that SW is not just a switch but also an element to interrupt the energy supply and R3 protects the micro-controller from overvoltage through PIN2.

also similar to switches on headphone cables and power switches for commands mentioned above, its implementation requires no switch.

We focus on two types of energy sources; coin batteries and PV modules, as these will continue to be the major energy sources for small devices. Prototypes based on battery holders and a PV module were developed and the input of commands was explored.

3.1 Schematic with Batteries

There are several methods to detect energy supply interruption. Considering techniques for small devices, it is important to minimize energy loss and consumption, lower the cost and size of additional elements, and occupy only a few pins of the micro-controller. One possible schematic is shown in **Fig. 3**. In the schematic, SW is not just a mechanical switch but also an element for interrupting the energy supply as will be described. The micro-controller uses two pins, one for output the other for input, to periodically monitor the energy supply state. During the monitoring phase, PIN1 outputs HIGH and the power for the micro-controller is supplied by the capacitor. When the energy supply from the battery is being blocked, i.e., SW in the figure is OFF, PIN2 as input becomes LOW, and vice versa. Note that R3 prevents the voltage applied to PIN2 from exceeding VCC, the driving voltage of the micro-controller (the PIN2 voltage would be equal to the battery voltage without R3), when the user stops the energy supply interruption and PIN1 is HIGH. Outside the monitoring phase, PIN1 is set to LOW, the capacitor is charged, and VCC is equal to the battery voltage (it is not strictly accurate because the P-MOS creates a slight voltage drop due to its ON-state resistance, but its effect is negligible since only a little current flows). The power consumed during monitoring (excluding micro-controller) is that consumed by the resistors, which can be minimized by using high resistance values. Additionally, monitoring duration can be shortened, thus the additional power consumption is negligible. Outside the monitoring phase, there should be no energy loss. Replacing the P-MOSFET with a diode and removing the N-MOSFET and R2 yields the simplest schematic that offers the monitoring function without using PIN1, see **Fig. 4**. Unfortunately, VCC would fall below the battery volt-
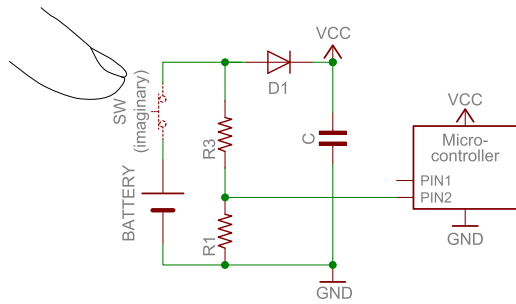
Fig. 4 Other example of a circuit. The N-MOSFET and R2 shown in Fig. 3 are eliminated and P-MOSFET is replaced by a diode. While this configuration is easy to implement and only one PIN is needed, there is energy loss because current always flow through R3 and VCC does not match battery voltage.

age and additional power would be continuously consumed.

One of the keys to this implementation design is the blocking element, shown as SW in the figure. If the device has a power switch, it can be used as a practical blocking element. It is possible to emulate a switch using the battery holder even when the device has no switch. Battery holders are used to hold the battery and ensure the electrical connections. Several forms of battery holders are available; some are called retainers and clips. The connection between the device and the battery is established by physically pressing the electrodes to the battery. This configuration is almost the same as a switch, suggesting that battery holders can work as switches.

There are some devices that do not have battery holders or direct access to their battery is blocked, such as soldered and molded connections. Unfortunately, the proposed technique can not be applied to such devices. Devices whose batteries are recharged wirelessly or via wired connections can accept both the proposed technique and regular PLCs.

3.2   Schematic with PV Modules

The technique can be implemented when a PV module is used as an energy source. Since a single PV cell generates only low voltage, multiple cells are connected in series to form a PV module. It is well known that the power generated by a PV module depends on the illumination level. The PV's current decreases when it is shadowed. **Figure 5** shows an example of the I-V characteristics of a PV module, Panasonic AM-1456, that consists of four amorphous PV cells, measured in a regular office environment of about 760 lx. The characteristics were measured under several illumination levels set by adding ND (neutral density) filters to the PV module. For example, an ND filter of OD 0.3 attenuates the light to 50% and OD 1.2 to 6%. The output current of the PV module is almost linear to illumination in the range of low voltage. The energy supply is blocked by shadowing the PV module. In the figure, two dotted lines that represent the I-V characteristics of 100 kΩ and 2 MΩ are also shown. When the resistor is connected to the PV module as a load, the intersection of the two curves corresponds to the PV voltage. For example, in the case of OD 0.3 and 100 kΩ, the intersection, red circle in the figure, indicates that the measured PV voltage is 1.3 V. Whether the energy supply is blocked or not is decided by comparing the measured PV voltage to a threshold, unlike the battery case.
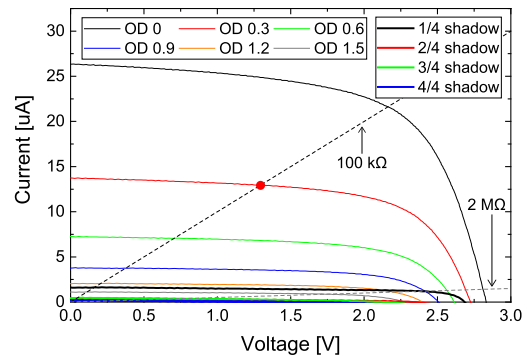

Fig. 5 An example of the I-V characteristics of a PV module, Panasonic AM-1456, consisting of four PV cells connected in series. The illumination level was adjusted by covering the PV module with ND filters. For example, an ND filter of OD 0.3 attenuates the light to 50%. The current is almost linear to illumination level. The graph also shows the characteristics when the PV module was partially shadowed. For example, 1/4 shadow corresponds to complete shadowing of one PV cell. Partial shadowing dramatically decreases power generation performance so that it falls below that of OD 1.2 (the light is attenuated to 6%). The dotted lines represent 100 kΩ and 2 MΩ. When the resistor is connected to the PV module as a load, the intersection point indicates the PV voltage, i.e., OD 0.3 and 100 kΩ yield 1.3 V.
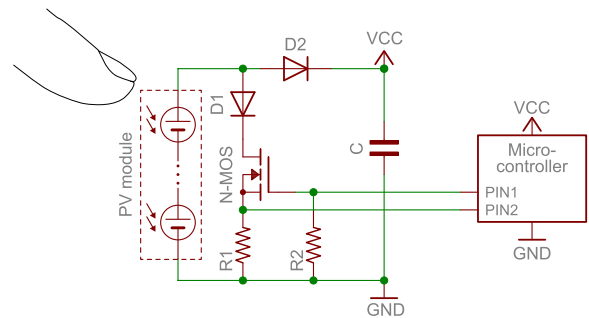

Fig. 6 An example of a circuit to detect energy supply interruption from a PV module. The micro-controller periodically monitors whether the energy supply is blocked. While there is clear difference between the battery is connected and disconnected in the battery case, there is no clear boundary indicating whether the energy from the PV module is blocked or not. Monitoring is realized by comparing the voltage of R1 to a threshold by a comparator embedded inside the micro-controller. Note that the diodes are inserted to prevent energy loss and protect the micro-controller, since the voltage of the PV module can vary widely.

The user can input commands by adjusting the illumination level. One example of a schematic that detects PV voltage drops is shown in **Fig. 6**. While there is no need to worry about the energy source shorting out in the previous battery case, the PV voltage falls to almost zero in very dark environments. Two diodes are used to prevent reverse current flows when the PV is almost shorted out and to protect the micro-controller from overvoltage through PIN2. The micro-controller uses two pins to periodically monitor PV voltage as in the battery case. When PIN1 outputs HIGH, R1 is added to the load of the PV module. A comparator, which is assumed to be embedded inside the micro-controller in Fig. 6, compares the voltage drop of R1 to the threshold.

The user can simply use her hand to shadow the PV-based device. One interesting feature of PV modules is partial shadowing [27]; the generated energy is dramatically decreased even if only one of the PV cells is shadowed because a shadowed PV cell acts as a diode. Figure 5 also shows the characteristics when a
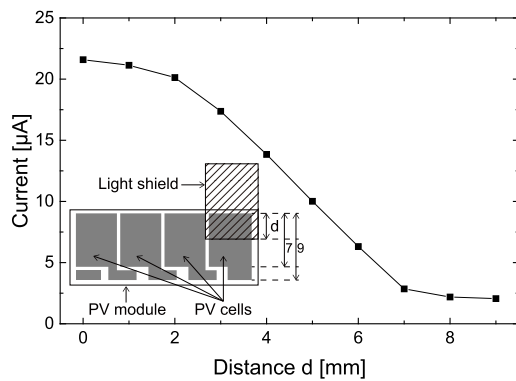
Fig. 7 Current output when one of the PV cells of the PV module was shadowed. The PV module was connected to 100 kΩ as a load. The current is sensitive with the degree of shadowing. Almost full shadow is required to make the current small enough to be properly detected as energy supply interruption.

Fig. 8 Developed initial prototypes. The left one is battery-based and the right is PV-based. Since they were developed to confirm the technique worked as expected, segmented LCDs were embedded to give feedback.

part of the PV module was shadowed. One to four cells among the four forming the module were shadowed; "1/4 shadow" in the figure corresponds to the case when one cell was shadowed and "4/4 shadow" indicates that all cells were shadowed. The current falls markedly if just one cell is shadowed and its level is below that with an ND filter of OD 1.2, less than 2 V. It is also indicated that the load of the PV module, R1, should not be high because the PV voltage under 1/4 shadow exceeds that with OD 1.2 when it has high resistance. Moreover, a higher R1 resistance creates a large time constant making the monitoring process wait a longer time until the PV voltage decreases enough. **Figure 7** shows another result for partial shadowing. In this experiment, the PV module was connected to 100 kΩ as a load and the current was measured when shadowing one of the four PV cells. The current is sensitive to the shadowing and decreases enough to be detected as blocking. Though this sensitivity to shadowing is generally considered to be a negative aspect of PV modules, it can be used positively as a touch sensor [18]. The proposed technique can also use partial shadowing positively. This feature is effective, especially when using physical barcodes as described later. When the threshold is set to the level with OD 1.2 in Fig. 5 (and with small resistance of R1), shading the whole PV module and shadowing just one cell are detected as energy supply interruption. While the former requires the use of the palm, partial shadowing is possible by finger interaction, which is more familiar to users and can increase the interaction speed.

3.3 Blocking Actions and Command Assignment

Actions suitable for inputting device commands were explored. The simplest action is to detach one of the connecting electrodes from the battery or shadow the PV module. Some simple tools could be helpful to make these actions more reliable and practical. For example, a thin insulating sheet such as paper or plastic sheet can be inserted between and removed from one end of the battery and the connecting electrode. Such sheets allow more types of battery holders to be used and they will save the user's finger and nail from being hurt. Since most objects block light, it is easy to completely shadow the PV module and so prevent miss-detection. These tools are already ubiquitous and are available whenever the user wants to input commands. Figures 1 and
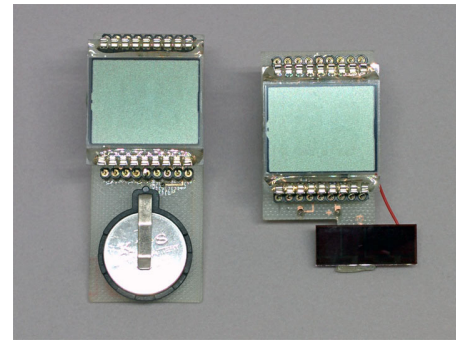
2 show examples of energy supply interruption with batteries and PV modules. When several contact points are implemented in the battery holder, isolating tape is used to limit them to one that is the target of the blocking action.

A series of sequential actions is recognized as a command. If the commands are represented numerically and the number of them is limited within some range, e.g., less than ten, counting the number of blocking events can directly specify the command. If the command space must be larger, encoding techniques decrease the time needed and errors created when inputting a command. While this realizes a larger command space, mental loads are increased because the user has to encode the command in his head. One practical solution is the use of Morse code. If the command is not suitable to represent numerically, blocking rhythm, i.e., gestures, can specify the command.

3.4 Initial Prototypes

Two prototypes, battery-based and PV-based, were developed to confirm the technique, see **Fig. 8**. Both prototypes used PIC 16LF1938 as the micro-controller and had segmented LCDs to give feedback. A coin type lithium battery, CR2032, was used for the battery-based prototype and an amorphous PV module, AM-1456, for the PV-based prototype. The PV-based prototype required two additional functions. One is to monitor VCC voltage and the other is to generate a reference voltage. The former is needed to prevent VCC from dropping below the micro-controller's range due to its operation or dark environment, and the latter is to keep the threshold at a constant value. If both PV voltage and its generating power are high enough, these functions are easily embedded by using a zener diode or a voltage regulator. The PV module used, however, did not generate enough power, especially in dark environments. We note that commercial PV-based calculators often include a battery to ensure proper operation. A small additional battery is a cheap and practical solution, but the PV-based prototype did not have a battery. Thus, these functions were implemented with low power consumption but without high precision. VCC was monitored and adjusted to lie within some range and used as the reference voltage. If VCC exceeded the range, some peripheral devices within the micro-controller were activated just to consume power until VCC fell into the range. If VCC dropped out of the range, the micro-controller made the sleep time longer to ensure voltage recovery.

The operation of the battery-based prototype was as follows. Initial monitoring, which checks whether interruption has started or not, was performed every 64 ms. Upon detecting blocking, monitoring was performed every 16 ms to eliminate false positives. The time durations of blocking or not were recorded until the energy supply continued for a period in excess of about 1.5 s, which was regarded as indicating the end of the command. Then, the prototype tried to decode the sequence, output the result on the LCD, and monitoring was returned to the initial phase. The PV-based prototype can suffer unintentional interruption due to environmental issues. An additional command that precedes the main command, shadowing for about 1 s, was implemented to avoid false positives. When the prototype failed to detect the preceding command, it discarded the following sequence. The prototypes were made just to confirm input functionality, so the micro-controller, run at 31 kHz, slept except when monitoring and changing the feedback on the LCDs.

Two decoding approaches; direct number of blocking events and Morse coding, were implemented. Energy supply interruption was performed by a finger nail or plastic sheet for the battery-based prototype and finger touch on a PV cell for the PV-based prototype. Both prototypes worked as expected, i.e., the user could input the desired digit(s). With the battery-based prototype, the monitoring process and following recovery of VCC took less than 2.5 ms when R1 and R3 had resistances of 1 MΩ and R2 had 10 MΩ, respectively, when 3 V was supplied. While the current flowed was dynamically changed, it corresponded to an average current of $8\,\mu A$ for the 2.5 ms duration and the energy consumed was calculated as less than 6×10^{-8} J for one monitoring process. The capacitance of C affects how long the micro-controller can work without energy supply. Its minimum driving voltage is 1.8 V and it consumes $0.8\,\mu A$ (typical value at 3 V) when sleeping. When 1, 4.7, and $10\,\mu F$ of capacitors were actually used, the time durations till the voltage dropped to 1.8 V were 1.0, 4.2, and 9.4 s. These changes in capacitance do not impact factor enlargement significantly. The additional elements including MOSFETs, resistors and diodes are cheap and their footprints are small, i.e., their total footprint is about $10\,mm^2$ in the current prototypes. They can be made even smaller. This indicates that the technique contributes to further miniaturization with negligible increases in cost and space.

Several interesting findings were obtained. When R1 in Fig. 3 was too high, the blocking actions by a finger were sometimes undetected because the resistance of the finger was less than that of R1. Isolating by the nail was effective in such case. Since detaching the connection involved pulling, rather than pushing, with the battery-based prototype, the action to generate Morse code was the opposite of that needed for regular Morse code key operation, which might cause some confusion. The developed PV-based prototype failed to detect the interruption properly under quite bright or dark environments. It was implemented assuming indoor use, where the illumination level is about 400–1,000 lx. Sunlight is so bright that the illumination level would be about 100 times stronger than that indoors, so the current prototype could not keep the voltage within the range needed. Moreover, when the illumination level was high, the prototype could keep
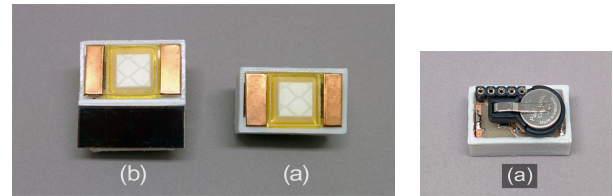

Fig. 9   Developed active tag prototypes; the battery-based tag (a) and the PV-based (b). The right figure shows the backside of the battery-based tag. They consist of a kind of liquid crystal, retroreflector, micro-controller, and power source to send tag IDs by switching the liquid crystal. A time-of-flight-based depth sensing camera that emits pulsed IR decodes the tag ID from the reflected IR modulated by the tag. Direct interaction provided by the proposed technique are used to change the tag state, sending the ID or not, and setting the tag ID.

the voltage, VCC quickly increased after it was adjusted, which increased the threshold and caused false positives. When the illumination level was 200 lx, the voltage recovery time was short enough to input commands. However, in darker environments, the voltage recovery process took a long time and energy interruption was often missed, which caused decoding errors. These failures can be solved by changing the monitoring durations adaptively based on the illumination level, using a large capacitance, battery-friendly sequences that consist of short shadowing and long bright durations, or fusing a steady voltage reference described later.

3.5   Application Example

Since the initial prototypes were large enough to mount switches and/or conventional input systems, the advantages of the proposal were not well demonstrated. To provide such a demonstration, we developed active tag prototypes.

Our previously proposed active tag [20] is a suitable example of how effective the proposed technique will be. The tag is read by a time-of-flight-based depth sensing camera and its wide readable range offers a practical solution to linking physical objects and information for ubiquitous computing. Ordinarily, the tag repeatedly sends its ID by switching the liquid crystal to modulate the light emitted from the depth sensing camera, and the user simply reads the ID. Occasionally, special commands are required, e.g., changing tag ID to avoid overlap and starting/stopping tag operation. These commands should be entered via direct interaction with the tag because if two tags have the same ID, the ID of only one of them should be changed. Stopping ID sending for days or weeks while no camera is available is effective to extend the battery life. Previously, the ID was changed by a wired connection, for which the tags were equipped with connectors. Additionally, a power switch was also used to turn on and off the tag.

Figure 9 shows the prototype tags with the proposed technique; one uses a lithium coin battery, CR1025, and the other uses a PV module, AM-1456. While the former used a PIC 12LF1840 as its micro-controller, the latter used a PIC 16LF1825 because more PINs were required, e.g., voltage doubler to activate the liquid crystal, monitoring VCC voltage. A minimum command set including resetting the ID and starting/stopping ID sending, was implemented. Since the number of IDs is currently limited to sixteen, simple command assignment was used; the new ID

was made equal to the number of short energy supply blocking events (minus one because the ID started at zero) and a single long blocking event was used to indicate command start and stop. The PV-based tag used a pre-command, long blocking, to prevent false positives.

The commands were successfully recognized and the ID and the state of ID sending could be changed simply. The proposed technique removes the need to embed a connector and a power switch and so offers further miniaturization. Note that the PV-based tag has a switch to reset the micro-controller to recover from improper operation, for example, when the illumination level oscillates around the threshold. Though both tags currently have connectors to change the program of the micro-controller, the connectors would be removed from production tags.

4. Discussion

We have confirmed that energy sources can be used as input systems to allow the user to directly interact with very small IoT devices. Several possible improvements are described below. One idea is re-designing the battery holders to suit interaction by the user's finger/hand. For example, extending the electrode in the battery holder for easy finger interaction. Another is a battery cover that normally connects the electric supply circuit but disconnects it when it is pushed.

Another idea is the use of tools. This will make it easier to implement complicated encoding schemes and expand the command space. As various fabricating techniques and machines such as laser cutters and 3D printers become more popular, the user can easily make his own customized objects. This trend will strengthen and effective tools for the proposed technique will be created quickly and cheaply. Two tools were fabricated; one is an electrical barcode for battery holders and the other is a physical barcode for PV modules, see **Fig. 10**. The former is a piece of paper on which a barcode is printed in conductive ink and conductive tape was attached to establish the electrical connectivity between the ink and the backside. Its dimensions are $9\,\mathrm{cm} \times 0.8\,\mathrm{cm}$, and weight is about $1\,\mathrm{g}$. The latter was built as an acrylic plate that blocks the light. Its dimensions are $12.5\,\mathrm{cm} \times 1.1\,\mathrm{cm}$, and weight is about $3\,\mathrm{g}$. Rows of holes made by a laser cutter were used to implement the code desired. This tool emphasizes the positive use of partial shadowing shown in Fig. 7. These tools generate encoded sequences of energy supply interruptions that correspond to commands. They were found to work but need further refinement (the ink was too fragile) or more training (difficult to keep the tool speed constant over long barcodes) to use as useful command input tools.

The operation of the current PV-based prototype tag depended on the surrounding illumination level. They sometimes worked improperly under quite bright or dark environments and the micro-controller needed to be manually reset, which thus demands the installation of a switch. Use of a steady voltage reference would improve the robustness of the PV-based device. While there are several possible solutions, for example, use of voltage reference inside the micro-controller or independent voltage regulator for bright environment, adding a small battery like most PV-based calculators is considered to be the most practical
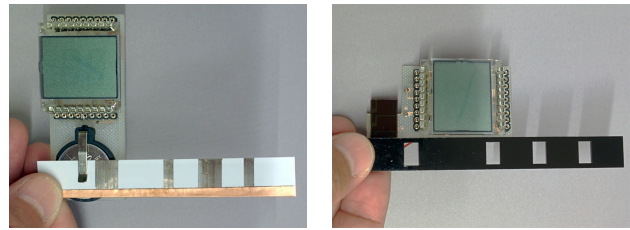

Fig. 10 Example of tools to realize complicated encoding. The left figure shows an electric barcode for battery-based prototype, the right a physical barcode for PV-based prototype. These tools are easily and cheaply created; the electric barcode was made using paper, conductive pen, and conductive tape, the physical one was made using a black acrylic plate and laser cutter. Commands can be input by moving the tools.

one if allowed.

The proposed technique allows the user to input commands via direct interaction and the prototypes confirmed that the technique works as expected. However, the technique is not truly mature as an input technique and further improvements are desired as mentioned above. When the technique is improved and embedded, the user will have two means to input commands to some of the small target devices; via the proposed direct interaction or indirectly via intermediary devices such as smartphones. It is important to investigate what kind of situations and commands are suitable for direct interaction and how many commands can be practically supported by direct interaction and how complicated they can be. The collaboration and division of roles of the two interaction approaches, direct and indirect, is an interesting topic for further research.

5. Conclusion

A technique that integrates a device's input system into its energy source was explored for further miniaturization of small devices. It uses the structures of battery holders and the characteristics of PV modules to interrupt the energy supply and thus emulate switches. Tests on two prototypes confirmed that the technique worked as expected and that it incurs very small additional power consumption and cost. It was also applied to active tags as a typical application and shown to improve the practicality of the tags. The proposed technique gives the user a way of directly interacting with small devices without increasing their size, power consumption, or cost.

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