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REGULAR PAPER

Easily-add battery-free wireless sensors to everyday objects: system implementation and usability study

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Abstract
The trend of IoT brings more and more connected smart devices into our daily lives, which can enable a ubiquitous sensing and interaction experience. However, augmenting many everyday objects with sensing abilities is not easy. BitID is an unobtrusive, low-cost, training-free, and easy-to-use technique that enables users to add sensing abilities to everyday objects in a DIY manner. A BitID sensor can be easily made from a UHF RFID tag and deployed on an object so that the tag's readability (whether the tag is identified by RFID readers) is mapped to binary states of the object (e.g., whether a door is open or closed). To further validate BitID's sensing performance, we use a robotic arm to press BitID buttons repetitively and swipe on BitID sliders. The average press recognition F1-score is 98.9% and the swipe recognition F1-score is 96.7%. To evaluate BitID's usability, we implement a prototype system that supports BitID sensor registration, semantic definition, status display, and real-time state and event detection. Using the system, users configured and deployed a BitID sensor with an average time duration of 4.9 min. 23 of the 24 users deployed BitID sensors worked accurately and robustly. In addition to the previously proposed 'short' BitID sensor, we propose new 'open' BitID sensors which show similar performance as 'short' sensors.

Keywords RFID · Wireless sensor · Internet of things · Deployment

1 Introduction

In the era of the Internet of Things (IoT), we are surrounded by more and more connected smart devices. Such devices can sense and report their states and provide ubiquitous interaction interfaces in smart spaces. However, most everyday objects are not smart, thus excluded from the picture. It is expensive and intrusive to replace existing objects with new smart devices.

BitID (Zhang et al. 2017) enables users to augment everyday objects with sensing and interaction abilities in a DIY manner. Users can modify a UHF RFID tag and deploy it on an object so that the tag's readability (whether the tag can be identified or not by an RFID reader) is externally modulated by the object state. The tag's ID can be read by the reader in one object state but not in the other object state. Such an external modulation scheme is referred to as 'ID Modulation' (Smith et al. 2005). Users can then sense object states and build input interfaces (e.g., buttons, sliders) using one or more BitID sensors.

Figure 1 shows the procedure of using a BitID sensor to detect whether a door is opened. The BitID sensor is made with a commodity off-the-shelf (COTS) UHF RFID tag and widely available tools like scissors and conductive tapes (Fig. 1a). The sensor is then registered in the system when put close to a reader antenna. A web-based interface is provided to define the semantic meanings of the sensor, including object name ('Door'), status mapping ('closed' when the tag is read and 'opened' otherwise). The BitID sensor is then deployed on the door with proper alignment so that its two parts will make contact when the door is closed. A message is sent to the smartphone when the door opens or closes.

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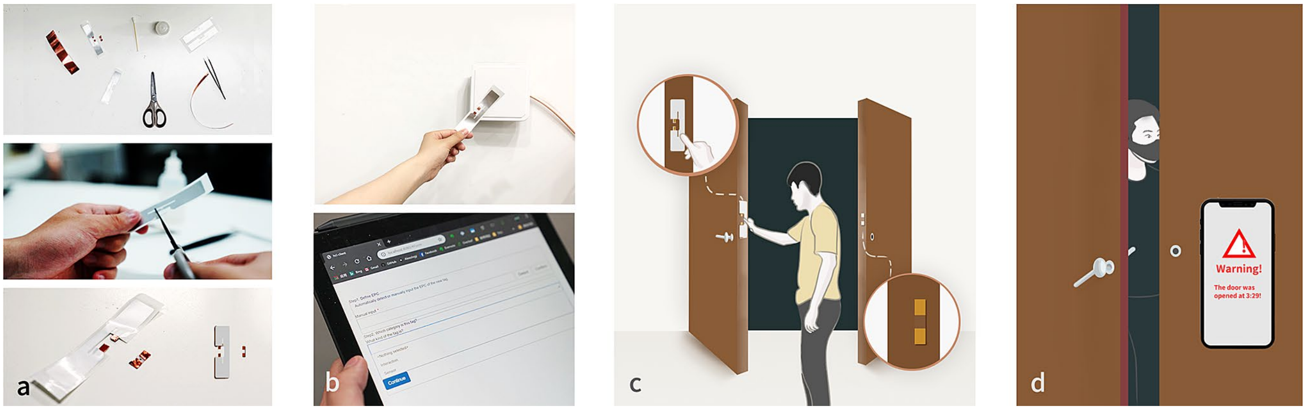

Fig. 1 **a** Sensor DIY making; **b** sensor registration and definition; **c** sensor deployment; **d** object status notification

Thanks to the flexible and thin form factor of UHF RFID tags, BitID sensors can be easily deployed on various objects and surfaces to enable ubiquitous sensing and interaction. The extremely low price (<$0.05 per tag) and the passive nature of RFID tags enable low-cost sensing solutions that do not require extra power maintenance. It also works without requiring a line of sight, which makes it especially suitable for monitoring the states of a large number of objects scattered at different places. Also, the user-defined sensing scope (binary states of objects) reduces privacy concerns compared to powerful sensors like cameras.

The previous BitID paper (Zhang et al. 2017) proposed to make BitID sensors by adding a shorting circuitry for the RFID IC (referred as *short* sensor henceforth) and demonstrated applications including security, energy monitoring, behavior tracking, fitness tracking, and input interface. However, the usage procedure of BitID is not clearly defined, and there lacks a complete system implementation. Thus the technique is not formally evaluated in terms of both *sensing performance* and *usability*.

In this paper, we first position BitID within existing tag-based sensing techniques. Then we briefly explain the sensing principle of two types of BitID sensors: (1) the already proposed *short* sensor; (2) *open* sensor, whose RFID IC and the antenna are connected in one state and separated in the other state of the object. Then we validated BitID's sensing performance by evaluating the sensing performance of BitID-based buttons and sliders. A robotic arm quickly changes sensor states to understand the boundary for the sensing mechanism used by BitID. We also implemented a complete prototype system that supports sensor registration, semantic definition, and real-time states detection and display. Using the system, we then evaluate BitID's usability by conducting a user study. The results show that users can successfully complete the sensing tasks using BitID sensors after watching demo videos. The average time spent to register, define, and deploy a BitID sensor is only 4.9 min. 23 out of the 24 participant-deployed sensors can accurately detect object states. The detection accuracy is 98.3% across all users for 7 objects that rapidly change states due to user interactions, which shows that the system is robust to behaviors from different users.

Our contribution is three-fold,

1. We built buttons and sliders using both *short* and *open* BitID sensors and validated that BitID works reliably and accurately with fast state changes.
2. We implemented and open-sourced a prototype BitID system, which supports sensor registration, semantic definition, and real-time sensor detection and display.
3. We conducted usability studies and validated that users can successfully and efficiently complete sensing tasks using the BitID system.

2 Background and related work

BitID analyzes signals emitted from modified RFID tags for sensing purposes. RFID technology has been used to enable ubiquitous sensing and interaction. Want *et al.* propose to bridge the physical and virtual worlds by placing RFID tags on various objects (Want et al. 1999). Users can also wear an RFID reader in the form of a glove (Philipose et al. 2004) or a bracelet (Fishkin et al. 2005) to recognize interactions with tagged everyday objects. The RFID-based sensing techniques use either the RF parameters (RSSI, phase) or the identification information of an RFID tag for sensing purposes. The section looks at RFID sensing techniques enabled by modeling RF parameters, then reviews techniques based on ID modulation. At last, we compare BitID with other reader-tag-based environment sensing techniques that use different signals like light and sound.

2.1 RF parameters modeling based RFID sensing techniques

The RFID reader can retrieve RF parameters (e.g., RSSI, phase, frequency channel) of each tag read, which can be used for various sensing tasks. Bhattacharyya *et al.* map the RFID tag structural deformation to its backscatter signal RSSI with empirically measured models. RFID tags are then turned into displacement sensors (Bhattacharyya et al. 2009). They later show relative differences of RSSI between two tags can be used to sense ambient temperatures (Bhattacharyya et al. 2010). The phase of a tag's backscattered signal changes linearly with the distance between the tag and reader antenna when only a direct path signal exists, which can be used for precise localization (Chang et al. 2018). Phases of RFID tag arrays can also be modeled to recognize gestures (Zou et al. 2017; Pradhan et al. 2017; Lin et al. 2015), reconstruct body-frame posture (Jin et al. 2018), track moving objects through walls (Yang et al. 2015), and detect illumination intensity (Wang et al. 2018).

Such modeling techniques can provide explainable results for a single sensing task. Recently, researchers apply modern learning models to the RF parameters for more complicated sensing tasks. By feeding statistics of RF parameters to end-to-end machine learning models, researchers can detect interaction gestures, infer daily activities, and track object movements (Li et al. 2015, 2016, 2019; Spielberg et al. 2016). Contact-free activity recognition can also be achieved by leveraging multipath information, and engineering phase-related features for a deep learning network (Fan et al. 2018; Wang and Zheng 2018).

However, RF parameters models require training and are environment-specific. Users need to retrain the model if the deploying environment is different from the training environment. The involved data collection and labeling demands can significantly reduce the user experience of such sensing systems.

2.2 Identification based RFID sensing techniques

Identification-based RFID sensing techniques do not require statistical models. The end users only need to configure the sensor once and then deploy the sensor properly. An RFID tag sends the stored ID information (EPC) to the reader by modulating the backscattered signal. The identification of a tag can be externally modulated so that the readability of the tag is used for different sensing tasks. For example, a temperature higher than a threshold can cause electrical changes of specially designed RFID tags. When the antenna structure of the RFID tag is changed, RFID readers cannot detect the tag anymore. Such temperature-sensitive tags can then be used to detect product spoilage due to temperature extremes (Want 2004). Smith *et al.* modulated a tag's ID by switching its antenna structure between two RFID microchips, and built a 1-bit accelerometer using one antenna, two microchips, and two mercury switches (Smith et al. 2005; Philipose et al. 2005). They later propose a Wireless Identification Sensing Platform (WISP), which can be integrated with various sensors, including touch panel (Sample et al. 2009), accelerometers (Buettner et al. 2009), ultrasonic sensors (Philipose et al. 2005), and cameras (Naderiparizi et al. 2015) can also be integrated on (Sample et al. 2007). RFIBricks (Hsieh et al. 2018) resolves geometry of built structure by applying separated RFID tags on each building block and monitoring the tags' identification information.

BitID sensors also leveraged the RFID tags' identification information for sensing purpose. Instead of switching between two microchips like WISP, BitID only uses one RFID tag for a sensing task. Compared to sensors like RFIBricks tags and α-WISP, BitID sensors can be easily made in a DIY manner by end-users using a COTS UHF RFID tag and widely available materials. The BitID sensor also maintains the thin and flexible form factor of UHF RFID tags, which can facilitate its ubiquitous deployment. However, there lacks of understanding of whether users can deploy such sensors correctly in a DIY manner. A good user experience is vital for the adaption of such sensing techniques. In this paper, we formally evaluate the sensing performance and usability of BitID, which provides insights into the practical usage experience of similar ID modulation enabled RFID sensors.

2.3 Other reader-tag based environment sensing techniques

Aside from RFID, researchers have used many other types of reader-tag systems for sensing purposes. ThermalTag is imaged and recognized by analyzing the reflected heat from the human hand (Zhang et al. 2020). It is also possible to backscatter acoustic waves undersea for communication and sensing purposes (Jang and Adib 2019). VibroSight (Zhang et al. 2018) analyzes reflected laser signals from tags to detect tag vibration, which can be used to infer human activities and object states. Even though the sensing range is shorter, BitID does not require a line of sight between the reader and tags like VibroSight. This makes BitID more suitable for complex environments like home and warehouse. BitID detects the relative movement of object components, which requires the placement of two sensor components while Vibrosight only requires the deployment of one sensor. However, the object state is directly mapped to the sensor reading state by the deployment for BitID. Vibrosight, on the other hand, detects vibration and then infers object states, which can introduce errors. BitID also does not require customized readers and works with existing commercial RFID readers and tags, which are more accessible to users.

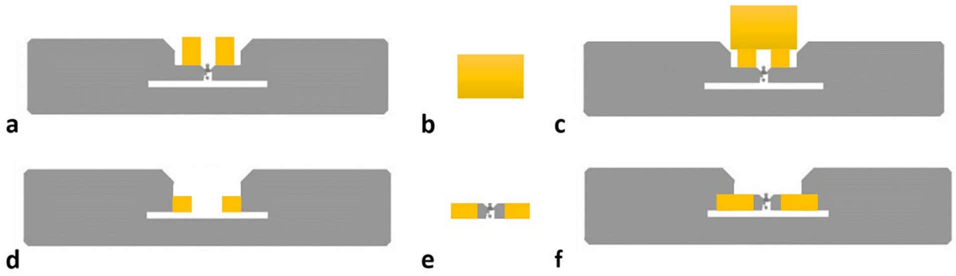

Fig. 2 Short sensor (**a**–**c**) and open sensor (**d**–**f**) made using AZ-9654 UHF RFID tags (grey) and conductive tapes (yellow)

3 BitID

In this section, we introduce the sensing principles of the *open* and *short* BitID sensors, as well as the real-time detection algorithm of BitID sensor states. Then we show the manufacture and deployment procedures of BitID sensors.

3.1 Sensing principle

A UHF RFID tag is identified by the EPC (the unique ID of the tag) stored in its microchip. The tag modulates the reader-generated interrogating signal by changing load impedance inside the chip according to the stored EPC. The amplitude or phase of the backscattered signal is then modulated. The reader then demodulates the backscattered signal to recover the EPC information and thus identify the tag.

We can use Differential Radar Cross Section (Rao et al. 2006; Nikitin et al. 2007) $\Delta\sigma$ to quantify the readability of an RFID tag.

$$\Delta\sigma = \frac{\lambda^2 G^2}{4\pi}|\Gamma_1 - \Gamma_2|^2 \qquad (1)$$

in which λ is the wavelength of the interrogating signal, G is the antenna gain, Γ_1 is the reflection coefficient of the chip with matched impedance, and Γ_2 is the reflection coefficient of the chip with mismatched impedance. A larger $\Delta\sigma$ indicates a cleaner modulation, which leads to easier demodulation by the reader. When $\Delta\sigma = 0$, the tag's modulation mechanism is completely disrupted, and the reader cannot identify the tag.

BitID sensors can switch between two states: in one state, $\Delta\sigma > 0$, the tag can be identified; in the other state, $\Delta\sigma \approx 0$, the tag cannot be identified. Users can then deploy the tag so that each state of the tag corresponds to a unique object state or interaction event. In this way, the modified tag is turned into a binary sensor, whose readability is determined by interaction gestures or object states.

BitID sensors can be categorized based on the mechanism used to modify $\Delta\sigma$. We introduce an *open* sensor (Fig. 2) and compare it with the previously proposed *short* sensor.

Short sensor The short sensor contains two parts: the tag part (Fig. 2a, referred as *Part A* henceforth) and the shorting part (Fig. 2b, referred as *Part B* henceforth). *Part A* adds two shorting strips beside the microchip, and can be identified by RFID readers. When the shorting strips of *Part A* are in contact with *Part B* (Fig. 2c), however, the reflection impedance of the chip becomes large all the time ($\Gamma_1 \approx \Gamma_2$), and the tag cannot be identified by RFID readers anymore ($\Delta\sigma \approx 0$).

Open sensor The open sensor also contains two parts: the antenna part (Fig. 2d, referred as *Part A* henceforth) and the microchip part (Fig. 2e, referred as *Part B* henceforth). The microchip in *Part B* is mismatched all the time ($\Gamma_1 \approx \Gamma_2$), and the gain becomes very small ($G \approx 0$), so the tag cannot be identified by RFID readers ($\Delta\sigma \approx 0$). The tag can be identified again when the two parts are correctly aligned and in contact (Fig. 2f).

RFID readers report the EPC and timestamps of each tag read continuously. The status of a BitID sensor can then be tracked using a sliding window. We encode the sensor status to '1' if the sensor's EPC is reported within the window, and '0' if it is not reported. In this paper, we use a sliding window of 0.2s and a step of 0.1s are used to detect BitID sensor states, which is empirically decided.

3.2 Manufacture

Figure 3a shows the stack of a typical wet inlay[1] UHF RFID tag. The inlay consists of an RFID microchip and the antenna structure, which modulates and backscatters the interrogating signal. Both short and open BitID sensors require exposure of the antenna structure, which can be achieved by either removing the PET/Paper film from the top of the adhesive layer from the bottom. In this paper, we remove the adhesive layer from the bottom to expose the antenna using alcohol and cotton stick, which we believe is easier than the previously proposed method to remove the paper layer from the top using a knife (Zhang et al. 2017). We use AZ-9654

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[1] Detailed explanation of RFID inlays can be found at https://skyrfid.com/RFID_Tag_Inlays.php.

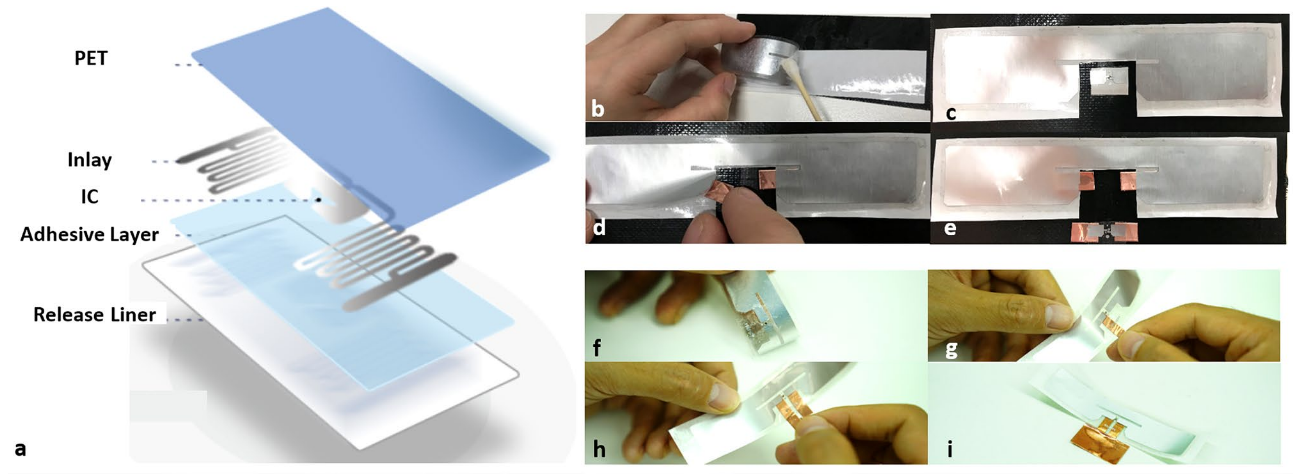

Fig. 3 The stack of a typical RFID tag (**a**) and manufacture procedure for both open sensor (**b**–**e**) and short sensor (**f**–**i**)

RFID tag to demonstrate the manufacturing process of both open and short BitID sensors.

Open sensor After the adhesive layer is removed (Fig. 3b), we cut off the microchip from the tag (Fig. 3c). Then we attach conductive tapes to the antenna structure as *Part A* (Fig. 3d), and to the microchip as *Part B* (Fig. 3e).

Short sensor After the adhesive layer is removed (Fig. 3f), we attach two conductive strips on each side of the microchip to form *Part A* (Fig. 3(g–h)). *Part B* can be any conductive materials as long as it can effectively short the two strips together. In Fig. 3i we use a piece of conductive tape as *Part B*.

3.3 Deployment

BitID sensors need to be properly deployed so that the tag's readability is uniquely mapped to the object status or the interaction event. For both open and short BitID sensors, the two parts of the sensor should be in contact in one state but disconnected in the other state. We categorize sensing tasks for BitID into two types: *Object Sensing* and *Interaction Sensing*. The object sensing tasks detect the binary state of everyday objects, while the interaction sensing tasks detect gestures like presses and slides.

Object Sensing The BitID sensor's *Part A* and *Part B* need to be placed on two components of the target object, which must involve relative movements during state changes. Lateral and longitudinal movements are two typical types of movement that users can look for when deploying a BitID sensor.

Interaction Sensing Users can build input devices like buttons, switches, and sliders with auxiliary materials. Such input interfaces can be deployed on everyday objects for a spontaneous and convenient input experience. We show exemplarily how to build BitID buttons and sliders in the next section.

4 BitID-enabled interaction interface

In this section, we first demonstrate the building procedure of BitID buttons and sliders, and explain the press and swipe events sensing mechanisms. We then validated the robustness of BitID sensors with both a robot arm and actual users. The physical test results also validate the BitID sensor's durability.

4.1 Building BitID buttons and sliders

Buttons are 0 DoF (Degree of Freedom) input interfaces that are widely used to toggle functions and even select objects (Zhang et al. 2017). Users can build a BitID button using one BitID sensor, and detect the press *event* based on the sensor *state*. Sliders are 1 DoF input interfaces that are also frequently used to adjust 1 DoF states (e.g., volume, brightness). Users can build a BitID slider using multiple BitID sensors, which detects the left and right swipe *events* based on *states* of the sensors.

We used plastic sheets to build the button and slider structures. Plastic sheets are elastic, low-cost, widely available everyday materials that can be easily cut or folded for DIY projects. Users can also use 3D printed buttons and slider cases to build such structures. Both press and swipe *events* are detected based on the time sequence of binary *states* of BitID sensors.

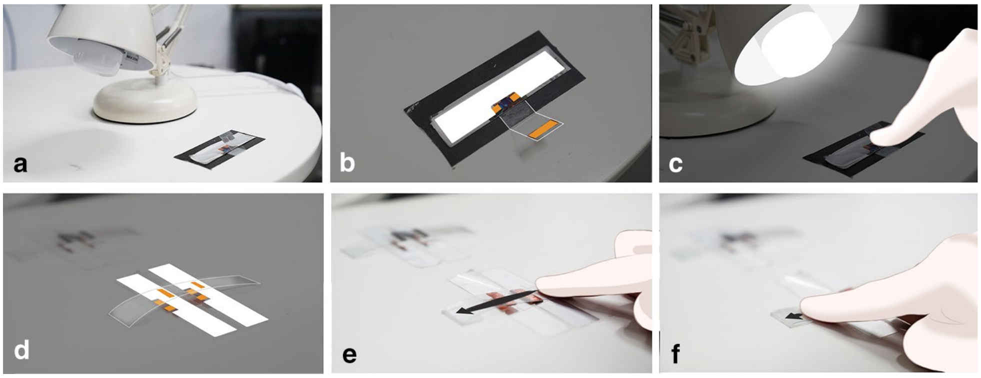

Fig. 4 A BitID button built with an open BitID sensor and a piece of plastic sheet (**a**–**c**). A BitID slider built with two short BitID sensors and a piece of plastic sheet (**d**–**f**). BitID sensors in the figures are touched up

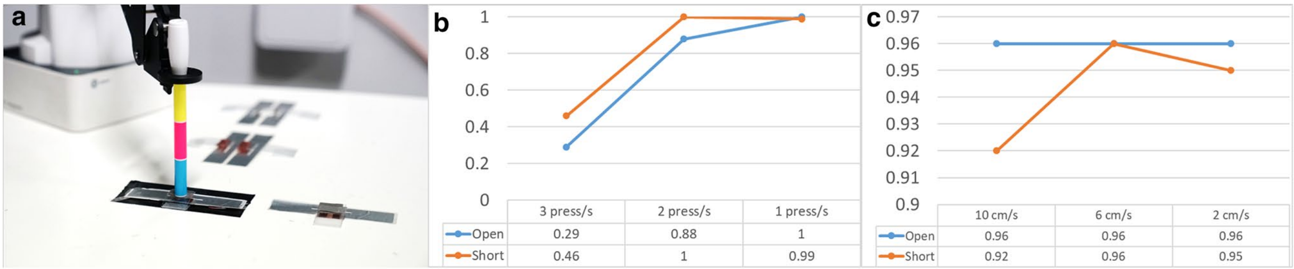

Fig. 5 **a** Experiment setup; **b** detection accuracy of BitID buttons; **c** detection accuracy of BitID sliders

- Button As shown in Fig. 4a–c, Sensor *Part A* is applied on a desk with a plastic sheet folded on top of it. The corresponding sensor *Part B* is then placed on the sheet in alignment with *Part A*, so that the two parts are in contact when the sheet is pressed down. We built two BitID buttons for evaluation, one with an open sensor and one with a short sensor. For an open sensor, a rising edge of its status sequence indicates a press event; for a short sensor, a falling edge indicates a press event.
- Slider As shown in Fig. 4d–f, we applied *Part A* of two BitID sensors side by side on the desk. Then we placed *Part B* of the two BitID sensors on a plastic sheet, aligned it on top of the two tags. The sheet was slightly bent and fixed so that it only contacts the desk during swipes. We built two BitID sliders for evaluation, one with two open sensors and one with two short sensors. The swipe gesture is detected by analyzing the time sequences of states of the two BitID sensors.

4.2 Physical test using a robot arm

We conduct physical test experiments to validate the durability of our sensors. We use a DOBOT Magician[2] robot arm with a pen to mimic human finger presses and swipes. The goal of the experiment is to understand BitID sensor's robustness for repetitive presses at different press rates and BitID sliders at different swipe speeds.

4.2.1 Experiment setup and procedure

The two BitID buttons, two BitID sliders, and the robot arm are all placed on a desk (Fig. 5a). Two 6 dBi antennas are placed orthogonally to collect tag readings, one in front of the desk and the other on the ceiling above the desk. Impinj R420 RFID reader is used to collect RFID data. Each BitID button is pressed 100 times at three different rates: 3 press/s (high), 2 press/s (medium), and 1 press/s (low). Each BitID slider is also swiped 100 times (50 right swipes, 50 left swipes) at three different speeds: 2 cm/s (slow), 6 cm/s (medium), and 10 cm/s (fast).

4.2.2 Results analysis

The detection accuracy is larger than 99% for both BitID buttons at the slow press rate (Fig. 5b). Buttons cannot support very fast presses (3 presses/s). The reason could be that the contact time between two sensor parts is too short for reader detection since the moving down and up of the plastic sheet consumes most of the time. The average detection accuracy under three swipe speeds is 96% for the open BitID slider and 94.3% for the short BitID slider (Fig. 5c). The results show that both sliders can robustly detect left and right swipes at both slow and fast speeds.

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[2] https://www.dobot.cc/dobot-magician/product-overview.html.

Table 1 Average real-time detection results of BitID buttons and sliders (Standard Deviation in parenthesis)

	Button		Slider	
	Open	Short	Open	Short
Precision	100% (0)	100% (0)	95.8% (3.91%)	98.1% (3.29%)
Recall	99.3% (1.30%)	96.5% (3.50%)	96.8% (3.18%)	96.5% (3.34%)
F1-score	99.6% (0.66%)	98.2% (1.84%)	96.2% (1.91%)	97.2% (1.87%)

4.3 User study

The robot arm can precisely control press rates and swipe speeds, but not the longitudinal pressures. We conducted a user study to evaluate the robustness of BitID buttons and sliders with natural press and slide pressures.

4.3.1 Experiment setup and procedure

We recruited 8 right-handed participants from the local institution with ages range from 22 to 30 (Mean = 24.8, SD = 2.6). Each participant was compensated 5 USD for their time. We used the same setup as described in Sect. 4.2.1.

We asked the participants to press 100 times of each BitID button using index fingers across four sessions (25 presses in each session). The participant was asked to “press naturally, as you would when turning on a light”. For the sliders, we asked the participants to swipe 100 times (50 right swipes and 50 left swipes) on each slider using index fingers across four sessions (25 swipes in each session). They were also asked to slide at a speed that they feel most comfortable and would use in daily tasks. The participants were allowed to press or swipe several times to get familiar with the setup. They were also allowed to rest between sessions.

4.3.2 Results analysis

We collected 800 presses data for each BitID button and 800 swipes data for each BitID slider. The real-time detection results are shown in Table 1. The average user press rate is about 1 press/s, while the swipe speed is around 8cm/s. The average F1-score is 98.9% for the two BitID buttons. More false negatives are detected than that in the robot arm experiment. The reason might be that the participants pressed less hard on the button, so the contact time between the two parts of BitID sensors was too short. The button structure can also introduce false positives. Even though the two components stop contact, it is still possible to pick up the tag signal when the sensor’s two components are very close to each other, especially with a strong interrogating signal from the reader. Such a phenomenon is explained in (Zhang et al. 2017) with a full-wave electromagnetic simulation. An improved press structure design should be able to mitigate both issues. Both sliders can accurately detect finger swipes in both directions and achieve an average F1-score of 96.7%. No significant differences are found between the two BitID buttons ($F_{1,7} = 4.12, p = 0.06$) and the two BitID sliders ($F_{1,7} = 0.98, p = 0.34$) by running One-way ANOVA, indicating a similar sensing performance of open and short sensors when used in input interfaces.

5 System implementation

In this section, we explain the system architecture (Fig. 6) and supporting functions for our implemented prototype system. We developed a cross-platform web-based front-end to register and define a BitID sensor. The back-end server then detects sensor states and provides feedback in real-time.

Web-based front-end The web-based user interfaces enable users to easily register and define a BitID sensor. It has four interfaces: the real-time BitID status display interface, the BitID sensor registration interface, and two sensor semantic definition interfaces. After the sensor is properly registered and defined, a JSON string is sent to the server.

Back-end server Our back-end software runs on a local PC server receiving data from the RFID reader under UDP protocol. The software has three layers: Data Layer, Semantic Layer, and Application Layer. The software detects BitID sensor status in real-time. It can understand and track the semantic events assigned to each BitID sensor, then return these events to the front-end application.

Both the front-end and back-end of our implementation are open sourced[3]. Below we explain in detail our front-end and back-end system design.

5.1 BitID front-end

Status display The status display interface is the default page so that users can easily check the status of all BitID sensors with an update rate of 5 fps. Users can click the ’Refresh’ button to update the BitID sensor list, and the ’Stop’ button to stop updating the states of the sensors.

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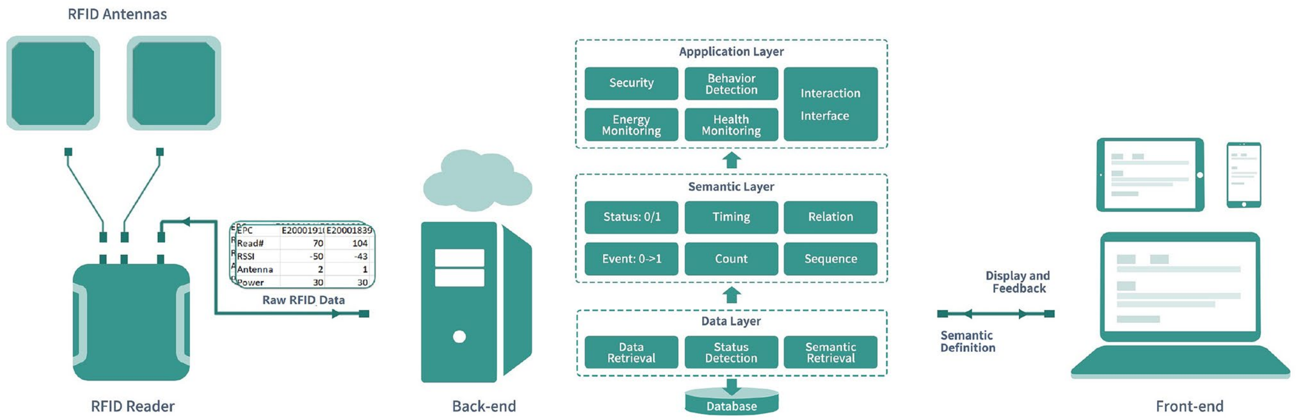
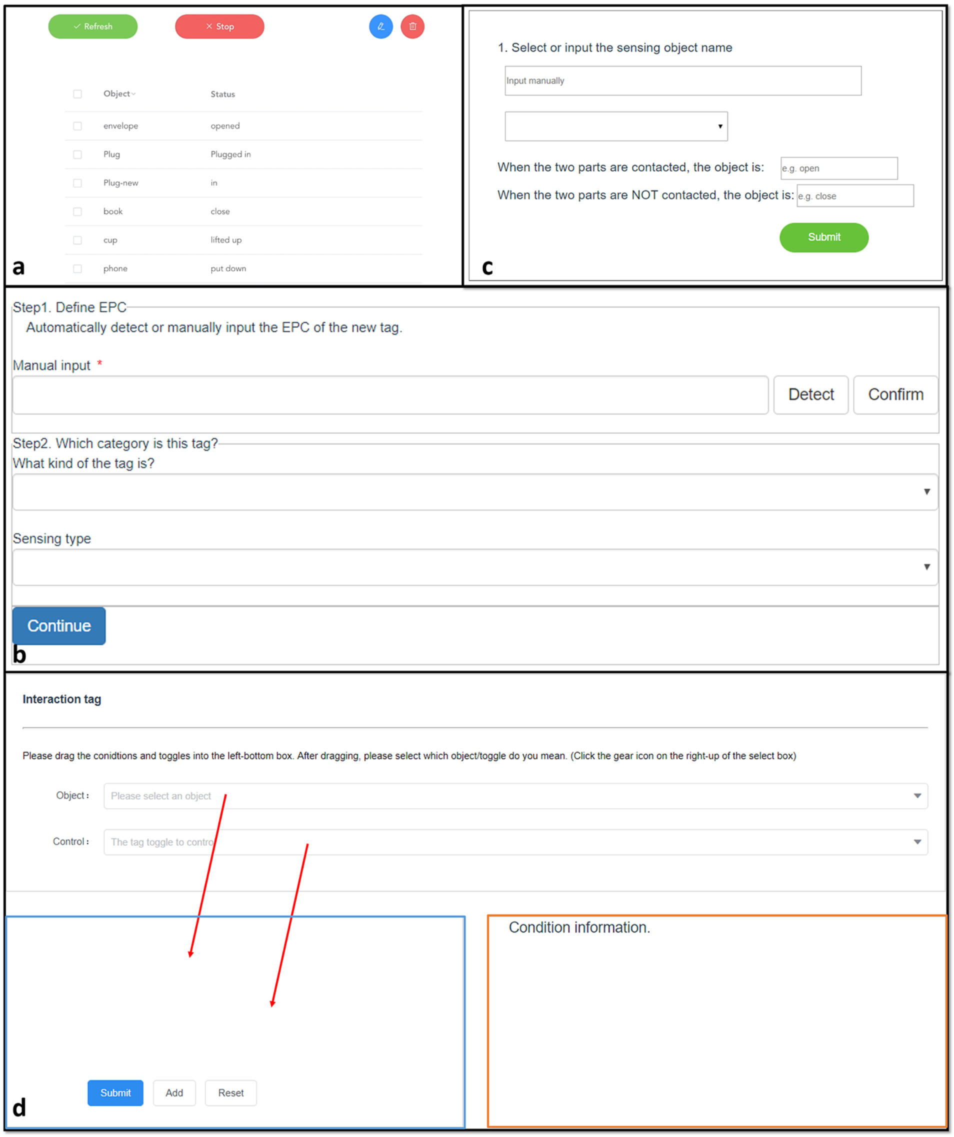
[3] https://github.com/AlexFxw/BitID.



EPC	E2000191(	E20001839
Read#	70	104
RSSI	-50	-43
Antenna	2	1
Power	30	30

Fig. 6 BitID system architecture



☐	Object	Status
☐	envelope	opened
☐	Plug	Plugged in
☐	Plug-new	in
☐	book	close
☐	cup	lifted up
☐	phone	put down

1. Select or input the sensing object name

Input manually

When the two parts are contacted, the object is: e.g. open

When the two parts are NOT contacted, the object is: e.g. close

Submit

Step1. Define EPC

Automatically detect or manually input the EPC of the new tag.

Manual input *

Detect Confirm

Step2. Which category is this tag?

What kind of the tag is?

Sensing type

Continue

Interaction tag

Please drag the conidtions and toggles into the left-bottom box. After dragging, please select which object/toggle do you mean. (Click the gear icon on the right-up of the select box)

Object: Please select an object

Control: The tag toggle to contro

Submit Add Reset

Condition information.

Fig. 7 Current interfaces for BitID sensor status display (**a**), registration (**b**), object sensor semantic definition (**c**), and interaction sensor semantic definition (**d**)

Users can register a BitID sensor by clicking the 'Edit' button on the top right corner of the page (Fig. 7).

Sensor registration The sensor registration interface navigates users to register BitID sensors. Users can turn on auto detect by clicking the 'Detect' button, which will automatically fill in the EPC of the tag that has the largest RSSI. They can then bring the tag close to reader antennas several times and click 'Confirm' once they are certain the correct EPC is filled in. Users can also type in the EPC manually. Then the users select the sensor types (object sensing or interaction sensing, open sensor or short sensor) and continue to define the sensor's semantic meanings.

Semantic definition We implemented two semantic definition interfaces depending on the task of the BitID sensor. 1. *Object Sensing*: After filling in the name of the target object (e.g. 'Door'), users can define the semantic meaning of the object status when the two parts of the sensor are contacted (e.g. 'open') or disconnected (e.g. 'closed'). The system will map the semantic definitions to the BitID sensor's state. 2. *Interaction sensing*: The BitID system functions as a self-sustained IFTTT[4] system for interaction sensors. Based on the states of current BitID object sensors, users can assign context-based functions to the BitID interaction sensor. Users can create rules by dragging conditions and control functions into the configuration window. The added rule will then appear in the rule window. Users can configure several rules for the same BitID input device.

5.2 BitID back-end

Data layer The data layer receives data from the RFID reader within the same LAN, as well as sensor semantics from the front-end. In addition, it maintains a list of registered BitID sensors' EPC to filter out unregistered RFID tags. Once a BitID sensor tag is detected, this layer will keep tracking its status. All the received and processed data including the raw RFID tag data, and status information is stored in the database. The data layer reports all tracked BitID sensor states and their semantic meanings to the semantic layer.

Semantic layer The semantic layer detects and understands the semantic meanings of all BitID sensors tracked by the data layer. For example, the system can detect button press *event* when the corresponding BitID sensor's *state* reverses. It can also time the state, conduct logic operations of states of multiple tags, count events, and record event sequences to understand semantic events such as (1) physical status of the object, (2) switch event, (3) changing speed, and 4) period of time the event lasts. For example, the sliding gesture is detected in this layer by processing event sequences of multiple BitID sensors.

Application layer Depending on the specific application, the application layer processes the semantic data and provides proper feedback to users. For example, an alert message can be sent to the user's phone when the door is opened. Another example is to generate a weekly report of the energy consumption of the lights monitored by a BitID sensor attached to the light switch.

6 BitID-enabled object sensors

The BitID sensor can be blocked by users during interactions, which can lead to incorrect sensing results. So we conducted a user study to evaluate our prototype system's performance when the user changes the states of the objects frequently in a behavior sequence. The study has three goals: (1) Validate that users can easily and successfully register, define, and deploy BitID sensors; (2) Validate robustness of BitID sensors on different objects with different user behaviors; (3) Collect subjective feedback to understand adoption challenges of the BitID system.

6.1 Participants and apparatus

We recruited 12 participants (9 males) from the local institution. Their ages range from 21 to 24 (Mean = 22.1, SD = 1.08). They were compensated with 15 USD for their time.

We set up the BitID system for a typical office desk. We use one RFID reader with two antennas, which are placed to cover the desk area orthogonally, one in front of the desk, the other hanging on the roof above the desk. We deployed 5 BitID sensors (3 short sensors and 2 open sensors) on typical objects on an office desk:

Book We deployed a short sensor inside the front cover of the book so that the two parts will separate when the book is opened, and remain in contact when the book is closed.

Line Phone We deployed the *Part A* of a short sensor on a line phone, and *Part B* on the headset. The two parts of the sensor will separate when the headset is picked up, and remain in contact when the headset is put down.

Cup We built a BitID button using an open sensor and a plastic sheet and applied it to the bottom of the cup. The 'button' will then be 'pressed down' when the cup is put down, and 'released' when lifted up.

Drawer We placed the *Part B* of an open sensor on a drawer and *Part A* on the drawer frame. The two parts

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[4] https://ifttt.com/.

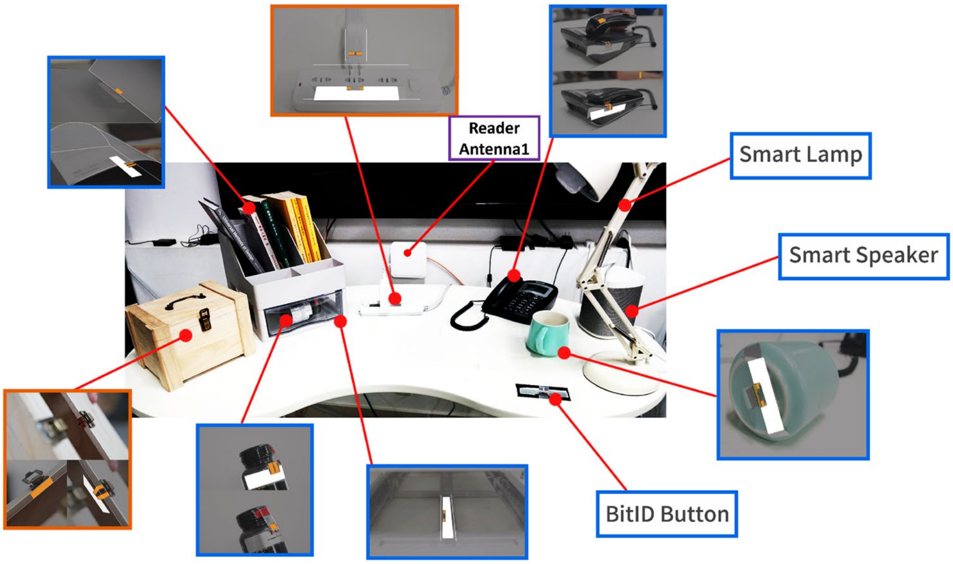

Fig. 8 Experiment Setup. The objects in blue frames were deployed by the experimenter, while the objects in orange frames were deployed by the participants. One of the reader antennas is indicated by purple frames. The other reader antenna is placed 1.5 meters on top of the desk on the ceiling

are aligned so that they will contact when the drawer is closed and separate when open.

Drug Bottle We applied a plastic sheet on the lid with the *Part B* of a short sensor and placed the *Part A* on the drug bottle. The two parts will separate when the lid is twisted open, and remain in contact when the lid is tightly closed.

The book is placed on a file shelf above the drawer. The drug bottle is placed inside the drawer. The line phone and the cup are placed on the desk.

We also added a BitID button on the desk as input. The button controlled two smart devices-a Yeelight LED bulb[5] and a Sonos speaker[6]. We assigned context-based functions for the button based on the status of the line phone. The button will mute/unmute the smart speaker when the phone headset is picked up, and toggle the LED bulb when the headset is put down (Fig. 8).

We also prepared tools for the two sensing tasks that participants need to complete during the study,

Wood Box We placed a wood box on the desk. A BitID sensor can be deployed on the box to detect whether its lid is open. An example deployment is shown in Fig. 8.

Charger and Power Strip We stuck a plug on the desk. A BitID sensor can be deployed on the power strip and a laptop charger to detect whether the charger is plugged in. An example deployment is also shown in Fig. 8.

The seven tasks are selected to show the versatility of BitID sensors. The seven activities involve BitID deployment on both portable (book, drug bottle, cup) and relatively fixed (box, drawer, landline, plug) objects. They include both lateral(drug box, drawer, landline) and vertical (cup, box, plug, book) deployment methods. The tag antenna is deployed on the curve surface for the drug bottle and flat surfaces for others. The cup and book deployment involve self-made supporting structures while others do not.

To mimic a real-world scenario, we recorded a demo video for participants to learn the sensor registration, definition, and deployment procedure (referred to as usage procedure henceforth) by watching it. The video shows detailed instructions on how to register and define a BitID sensor, as well as two sensors deployment examples-an open sensor to detect whether an envelope is sealed, and a short sensor to detect whether a book is opened. We provided already manufactured BitID sensors for the sensing tasks. A short sensor was provided for the box task, and an open sensor was deployed for the charger task.

6.2 Experiment design and procedure

Upon arrival, the participant first completed a demographic form. Then we explained the working principle of BitID system and asked the participants to use BitID sensors to complete two tasks: (1) Detect whether a wood box is open; (2) Detect whether the charger is plugged in the power strip. The participant then watched the demo video to learn the usage procedure of BitID. The participant can review the demo video and observe the already deployed BitID sensors on other objects during the period. After deployment, the participant validated the sensor functioned properly, then closed the box and plugged in the charger. The whole usage procedure was timed for each sensing task. The sequence of the two sensing tasks is balanced by Latin Square. The

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[5] https://yeelight.com/zh_CN/product/wifi-led-c.

[6] https://www.sonos.com/en-us/shop/play1.html.

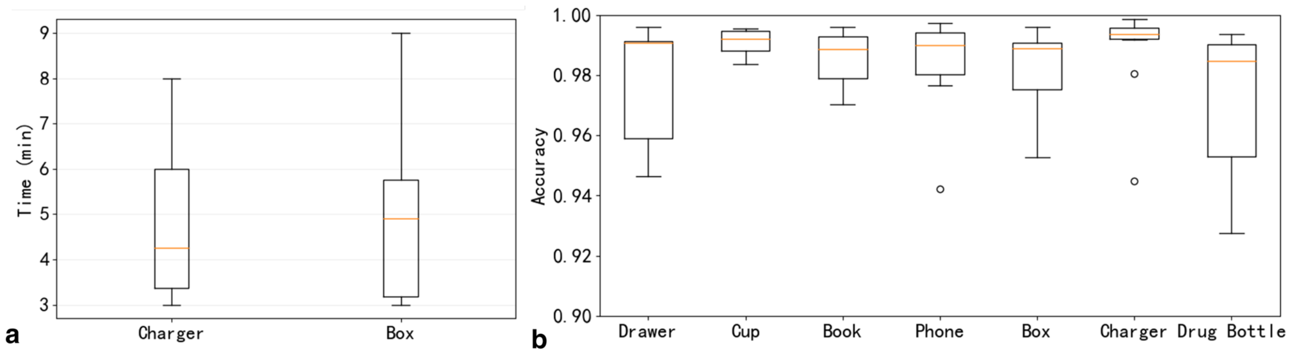

Fig. 9 **a** The usage procedure time boxplot for the charger task and the box task; **b** The detection accuracies for the 7 objects

participants rated the perceived easiness and time consumption of the whole BitID usage process using a 7-point Likert scale after completing the tasks.

We then asked the participant to conduct a behavior sequence for four sessions. Within each session, the participant finished four blocks of tasks-*Take Medicine, Read Book, Answer Phone, and Deployment Validation*.

Take Medicine Open the drawer, take out and open the drug bottle, pretend to drink from the cup, close and put back the drug bottle, then close the drawer.

Read Book Press the BitID button to turn on the lamp, pick up and open the book, read a while, close and put the book back, then press the button to turn off the lamp.

Answer Phone Pick up the phone, press the BitID button to mute the smart speaker, press again to unmute, then put down the phone.

Deployment Validation Open the box for a while, close the box, pull out the charger for a while, then plug it back in.

The sequence of the blocks within each session was balanced with Latin Square. The experimenter recorded the states of the objects by pressing SPACE on a laptop when a status change happened. The whole process was video recorded for later review. In the exit interview, the participants rated various usability factors that may impact their usage of the BitID system in a 7-point Likert scale (the higher, the better).

6.3 Results analysis

All participants successfully completed the charger task. 11 participants placed *Part A* on the power strip and *Part B* on the charger, while one participant adopted a reversed strategy (Fig. 8). All participants deployed the *Part A* on the box body and *Part B* on the lid (Fig. 8) except P7. The average registration, definition, and deployment time is 4.8 min (SD = 1.8) for the charger task, and 5.1 min (SD = 2.0) for the box task (Fig. 9a). Three participants mentioned that it was difficult to align the two parts of the sensor in the charging task, which could explain the longer time spent to complete the task. However, we observed that two participants figured out an alignment strategy to speed up the process. They peeled off the release liner of *Part B* and placed it on *Part A* on the power strip with the adhesive side facing outward, then plugged in the charger. *Part B* was then conveniently stuck on the charger with proper alignment. Several participants also spent more than 1 min peeling off release liners, which indicates improved tools can speed up the deployment.

We collected 6140 s (around 102 min) data during the behavior sequences. We double-checked the recorded video to ensure the ground truth data was correct. The records are then compared with the detected BitID states data. In the *Deployment Validation* block, the average charging status detection accuracy is 98.9%. For the box sensing task, however, the detection accuracy of the sensor deployed by P7 is only 32.8%, while the average accuracy for sensors deployed by other participants is 98.1%. We found that one sensor deployed by P7 passed the confirmation right after the deployment, but was not functioning in later validation blocks. This indicates a more rigorous confirmation protocol right after deployment is necessary. This malfunctioning sensor was easily fixed by P7 later though.

The overall detection accuracy for the 7 BitID sensors is 98.3% (excluding P7 box data point, Fig. 9b). The 1.7% error rate indicates that the BitID system only has an 8.7s status mismatch with the ground truth of 7 objects during the 16 behavior blocks for each participant. The less than 100% accuracy can be caused by detection delays and unintentional object status changes. For example, we observed that the drug bottle may roll within the drawer, which may impact the contact between the plastic sheet and the drug bottle. The tag antenna's performance is also degraded since it is bent (Siden et al. 2001), which makes it harder for the

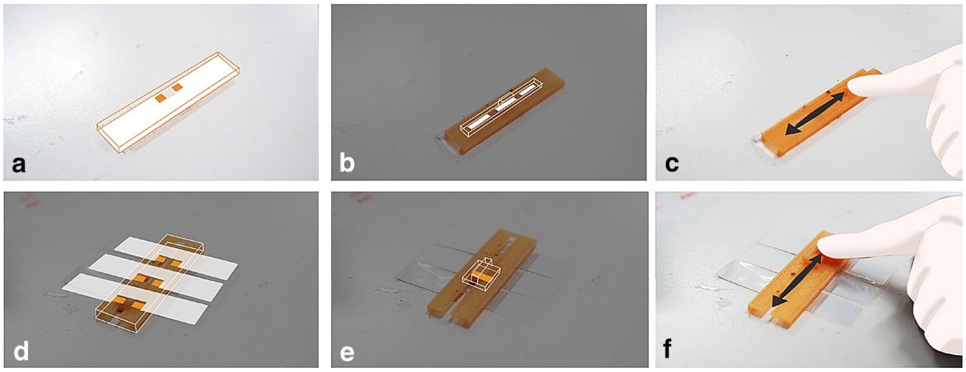

Fig. 10 BitID SP3T switches built with 3D printed cases. Note that the total area when using an open sensor (**a**–**c**) is only $\frac{1}{3}$ of that when using short sensors (**d**–**f**)

reader to demodulate the backscattered signal. Such reasons could explain the lower detection accuracy of the drug bottle status. The above results show that BitID can accurately detect object states even when the states are changed frequently. We also collected detection results of the 7 objects with BitID sensors for 6 straight hours. As expected, the detection accuracy for static objects is 100%.

Subjective ratings show that most participants (11/12) felt it was easy to use BitID sensors (MEDIAN = 7). They felt the deployment (MEDIAN = 5.5) was more difficult than the registration and definition (MEDIAN = 6.5) process. As expected, the participants felt it was easier to deploy the short sensors (MEDIAN = 6) than the open sensors (MEDIAN = 5), since the open sensors require a more precise alignment. Most participants (11/12) considered the context-based BitID button very useful (MEDIAN = 6). P3 mentioned, "I wish the button's function can be spontaneously defined instead of predefined". The participants felt *sensing robustness* (MEDIAN = 6.5) is a more important factor when considering BitID system adoption. *Easiness to use* (MEDIAN = 6) and *cost* (MEDIAN = 6) are also important, while *aesthetics* is a lesser concern (MEDIAN = 5).

7 Discussion

7.1 DIY or toolkit

In this paper, we deliberately used everyday materials like alcohol and plastic sheets to show that BitID can be manufactured and deployed in a DIY manner by end-users. Users may prefer DIY in some cases. For example, manufacturing and deploying BitID sensors could be a good family activity (Woo and Lim 2015; Sas and Neustaedter 2017). However, it is difficult to DIY BitID sensors with consistent and robust performance since the materials used during both manufacture and deployment can be different. 3D printed parts like button cases and slider rails can help simplify the deployment process, thus enabling more consistent sensing results. For example, SP3T (Single Pole 3 Through) BitID switches can be built with standard 3D printed cases rather than plastic sheets (Fig. 10). A universal 3D model library can be provided so that users can print standard auxiliary structures for sensor deployment.

7.2 Open vs short

The open and short BitID sensors are different in many ways,

Sensing Principle The open sensor is activated(readable) when its two parts are contacted, while the short sensor is activated when its two parts are separated. Both sensors' working range depends on the cutting or shorting position.

Manufacture The most time-consuming manufacturing step is the exposure of antenna and attaching conductive strips, which is required for both open and short sensors. Based on our experience, the two types of sensors have similar DIY complexity. A development kit with pre-separated BitID parts can be provided to alleviate the user manufacture burden.

Size One advantage of open BitID sensors is that multiple *Part B* can share the same *Part A*, so the size of input interfaces made by multiple open BitID sensors can be smaller. For example, the size of the BitID switch made with open BitID sensors (Fig. 10a–c) is only one-third of the switch made with the previously proposed short BitID sensor (Zhang et al. 2017) (Fig. 10d–f)).

Deployment The deployment of the short sensor is easier since it does not require precise alignments of the shorting strips and the conductor. The open sensor, on the other hand, usually requires precise alignments since the contact areas of its two parts are small.

Security Another advantage of open BitID sensors is that they are more suitable for security applications, in which BitID sensors are usually in contact state when the object is sealed or closed (e.g., door, box, envelop). During frequency channel jam attacks, the RFID reader is not able to identify any tag. There will be no state changes reported if short sensors are used. When using open sensors, on the other hand, the system will report a state change the moment the jam starts and send alerts to users.

7.3 Multi-tag interference and scalability

BitID sensing system can scale to a large number of sensors since RFID does not require a line of sight for tag identification. The RFID reader allocates time slots to send out interrogating signals. Tag collision can happen when more than one tag is energized within the same time slot. The reader then adopts anti-collision mechanisms to avoid tag interference. BitID works as long as the sensor is read successfully within the sliding window (0.2 s in our system). The Speedway R420 RFID reader we used in the evaluations can have up to 1100 tag reads per s and cover $144m^2$ area in Max Throughput mode. In theory, the reader can support a maximum of 220 BitID tags within a 0.2s sliding window. So it is highly unlikely that the tag failed to be read during an interaction that lasts more than 1 s. However, many factors can affect an RFID tag's readability. Large distance and polarization mismatch between the tag and the antenna will reduce the read rates (Nikitin and Rao 2006; Buettner and Wetherall 2008). Multiple antennas that cover different angles and areas can improve the readability of RFID tags. In this paper, we found that it was necessary to have two antennas pointing at orthogonal directions to mitigate the polarization mismatch of the tag's and the reader's antennas. It is also possible to deploy more than one RFID reader to improve signal coverage. For example, RFID readers can be integrated within ceiling lights to increase the BitID's coverage (Gummeson et al. 2017).

7.4 Generalizability

The manufacturing process of BitID requires exposure of antenna structures around the IC chip. RFID tags that have a relatively large connection area with the IC chip can speed up this step. The antenna structures should also not block the conducting strips. AZ-9654 RFID tags used in this paper are a perfect example of UHF RFID tags that are suitable for BitID customization.

BitID modifies COTS UHF RFID tags as sensors and uses RFID readers to collect ID information. The RFID reader, however, is not widely available in everyday settings. Recent research shows that smartphones can be used as readers for Bluetooth (Ensworth and Reynolds 2017), WiFi (Zhang et al. 2016), and FM (Wang et al. 2017) backscatter sensors. It is straightforward to scale BitID's sensing mechanism and usability results to such Bluetooth or WiFi backscatter sensors.

The status detection sliding window length is also dependent on the tag read rates. For example, the minimal BitID tag read rates should be larger than 5 reads/second to use a 0.2s sliding window. For more robust sensing, the BitID system can adjust the sliding window length on the fly based on current tag read rates.

8 Limitations and future work

BitID can only detect object state changes that involve relative movements. For example, there is relative movement when a light switch is turned on, so a BitID sensor can be deployed to detect whether the light is on knowing a default state. However, BitID cannot detect the light status if someone toggles the light with a remote. It is possible to integrate passive sensors with impedance output onto the RFID tag's antenna. For example, a phototransistor can be placed in serial connection with the IC chip (Wang et al. 2018). Phototransistors have a smaller resistance with light on and a much larger resistance with lights off, which can be approximated as a switch. The ID of the tag then can only be read when the light is on, which turns such a BitID into a binary light sensor. We plan to look into opportunities that integrate such binary sensors for advanced sensing purposes.

Even with toolkits, the user deployment process may still affect the robustness of BitID sensors. One way to improve robustness is to add redundant BitID sensors for the same sensing task. For example, the user can deploy three BitID sensors on a door and determine its state by majority vote. The system can also alert the user when different BitID sensors on the same object show contradicted results. The user can then fix the sensor accordingly.

The purpose of the in-lab studies in this paper is to understand the BitID system's practicality and usability during registration, configuration, and deployment, which does not require a large number of participants. A large-scale in-the-wild longitudinal user study is still necessary to evaluate BitID in a more realistic environment with more electromagnetic interferences, object occlusions, and people moving around. Such a study is out of the scope of this paper though, which we plan to carry out in the future.

9 Conclusion

In this paper, we explained the manufacture and deployment procedure of both *open* and *short* BitID sensors. We validated the sensing performance of BitID by evaluating BitID buttons and sliders using both a robotic arm and through a user study. The results show that the two types of BitID sensors have similar sensing performance. The average F1-score is 98.9% for finger presses and 96.7% for finger swipes. We then implemented a prototype system, including web-based interfaces and a server. We conducted a user study using the system to evaluate BitID's usability. The results show that users can complete the registration, definition, and deployment of a BitID sensor using an average time of 4.9 min. Out of the 24 user deployed sensors, 23 sensors could accurately and robustly detect states of the objects in later validations. The overall detection accuracy for seven objects that frequently change state is 98.3%. Our work can offer insights into the usability of future whole-home sensing systems manufactured or deployed in a DIY manner.

JSON Format

Object Sensing BitID

The below JSON string shows an open BitID sensor applied on a drawer. When the tag is identified ('ON'), the drawer should be closed; when the tag is not identified ('OFF'), the drawer should be opened.

```
{
  ”EPC”: ”E20000193907001913100929”,
  ”TagType”: ”Sensor”,
  ”SensingType”: ”open”,
  ”Semantic”: [
    {
      ”RelatedObject”: ”Drawer”,
      ”ON”: ”Close”,
      ”OFF”: ”Open”
    }
  ]
}
```

Interaction sensing BitID

The below JSON string shows a short BitID button that toggles a smart LED bulb when the headset of a phone is put down, while toggles the mute setting of a smart speaker when the headset of the phone is picked up.

```
{
  ”EPC”: ”E20000193907001913100535”,
  ”TagType”: ”Interaction”,
  ”SensingType”: ”short”,
  ”Semantic”: [{
          ”condition”: [{
              ”object”: ”phone”,
              ”semantic”: ”phone put down”
          }],
          ”toggle”: [{
              ”object”: ”light”,
              ”control”: ”power”
          }]
      },
      {
          ”condition”: [{
                  ”object”: ”phone”,
                  ”semantic”: ”phone picked up”
          }],
          ”toggle”: [{
              ”object”: ”speaker”,
              ”control”: ”mute”
          }]
      }
  ]
}
```

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Availability of data and material The data that support the findings of this work are available from the corresponding author, Yuntao Wang, upon reasonable request.

Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Code availability The source code of both the front-end and back-end of the implemented BitID system is open-sourced at https://github.com/AlexFxw/BitID. The source code for user studies is available from the corresponding author, Yuntao Wang, upon reasonable request.

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