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RESEARCH ARTICLE

MagID: Enhancing the Functionality of Off-the-Shelf Smartphones Through Magnetic Accessory Identification

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ABSTRACT Since the release of MagSafe, which allows magnetic attachment of accessories to smartphones, many vendors have introduced various kinds of MagSafe accessories, including wireless chargers, wallets, car mounts, and coolers. In light of this trend, we introduce MagID, a novel interface to connect physical accessories with software functionalities. For example, when an accessory (e.g., a car mount) is attached, it automatically invokes a specific application (e.g., a navigation app) or performs a certain task that corresponds to the accessory. The main idea of MagID for supporting this functional connection is to identify when and which accessories are attached to or detached from a smartphone. More specifically, based on our observations that MagSafe accessories have different magnetic properties from each other, we design a magnetic sensing-based accessory identification method and further improve its robustness with the combined use of non-magnetic features, e.g., accelerometer, gyroscope, and battery state readings. Our extensive experiments with a prototype implementation of MagID demonstrate that MagID can identify MagSafe accessories with high accuracy on any MagSafe-enabled smartphone and even in noisy environments, while not compromising usability.

INDEX TERMS MagSafe, smartphone accessory identification, magnetic sensing, sensor fusion.

I. INTRODUCTION

MagSafe [1] is a magnetic technology introduced for Apple's iPhone 12 and subsequent models to enhance wireless charging efficiency. A key enabler for the enhancement is a *MagSafe ring*, a circular array of magnets integrated into a smartphone and a charger. It allows seamless attachment of the charger to the smartphone's back with perfect alignment for charging. Note that according to WPC (Wireless Power Consortium) [2], MagSafe will be incorporated into the next generation standard for wireless charging, called Qi2, and will come to non-Apple devices (e.g., Android smartphones manufactured by various vendors).

This magnetic technology also has created a whole new world of accessories, including not just chargers but also battery packs, wallets, car mounts, coolers, and camera lenses. Equipped with magnets, these MagSafe accessories easily and securely snap onto the back of a MagSafe-enabled smartphone and thereby increase the smartphone's functionality. For example, imagine someone going on a road trip with a MagSafe smartphone. During driving, he can safely navigate using the smartphone mounted on a magnetic car holder. Once arrived at a historical site, he would want to capture the memorable moment or shop for souvenirs. To this end, he can just attach a magnetic camera lens (to take high-quality photos) or a magnetic wallet (to carry credit cards for shopping) to the smartphone.

In this work, we aim to further widen the functionality of smartphones by introducing MagID, an interface to support not just physical but also functional connection of the smartphones with MagSafe accessories. Fig. 1 illustrates procedures to set up and use MagID. A user first registers a

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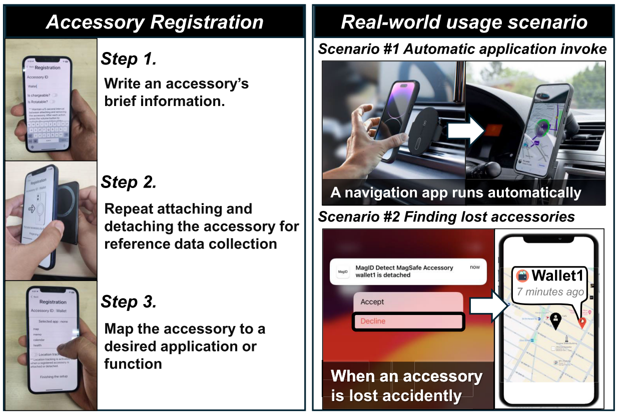


FIGURE 1. Usage scenarios of MagID.

MagSafe accessory to his/her smartphone and selects a combination of applications and functions to be performed when the accessory is attached or detached. After the registration, MagID automatically triggers the selected functions when the user connects or disconnects the registered accessory. That is, MagID enables users to freely map magnetic accessories to smartphone applications and functions, thus introducing intriguing usage cases. For instance, consider the traveler scenario described above. He will feel convenient with a camera or navigation app automatically launched when connecting a magnetic camera lens or car holder to his smartphone, respectively. As another example, it would be possible to dynamically adjust performance options for mobile games, e.g., changing screen brightness and rendering quality, depending on the attachment status of a magnetic cooler accessory.

A fundamental requirement for MagID to enable the functional connection is to accurately identify when and which accessory is attached to or detached from a smartphone. Interestingly, Apple smartphones are already capable of identifying MagSafe accessories by reading an NFC chip embedded in the accessories [3]. However, this advanced feature is supported only for accessories licensed by Apple, called Made-for-MagSafe accessories, not for MagSafe-compatible accessories from a variety of third-party manufacturers. Conversely, we propose an accessory identification method that can be adopted for any kind of commercial MagSafe accessories. This universal method is based on our observation that the magnets built into different accessories have slightly different shapes and strengths. In other words, each accessory has a unique magnetic signature. Inspired by this, we develop a magnetic sensing method that utilizes a smartphone's magnetometer to *i*) detect sudden changes in the magnetic field around the smartphone caused by the attachment or detachment of magnetic accessories, *ii*) extract their magnetic signature, and *iii*) identify them by comparing the signature with that of pre-collected reference data.

However, in practice, it is much challenging to accurately identify MagSafe accessories with this simple magnetic-based method due to the following reasons. First, the magnetic field vectors, we call them as magnetic signals, sensed by a smartphone's built-in magnetometer can also vary due to changes in the device's orientation and location. This means that the magnetic signature of accessories can be distorted in the presence of user movements or in dynamically-changing environments. In addition, accessories, which can be attached to a smartphone in any orientations, have different magnetic signatures depending on their attachment orientation. One naive solution to address these challenges is to build a reference data set under considerations on all possible noisy environments and attachment orientations, but losing usability.

Instead, we enable accurate, robust, and usable accessory identification with a novel design of MagID as follows.

- We pinpoint the occurrence of accessory attachment and detachment and extract noise-robust, i.e., environment-independent, signatures by collaboratively using various sensor data, such as a smartphone's magnetometer, gyroscope, accelerometer, and battery state readings.
- We collect a set of reference data by asking users to attach and detach accessories only 5 – 10 times. Also, for accessories that can be attached in any orientations, we give an additional but simple instruction, such as rotating them after attachment, to increase the diversity of their reference data set. It is noteworthy that this reference data collection is required only once when an accessory is newly registered.
- We classify accessories using a lightweight 1-Nearest Neighbor model and provide feedback, e.g., application activation, without a noticeable user latency.

We implement a prototype of MagID as a standalone iOS application and evaluate its performance in real-world environments. Our experimental results show that MagID accurately identifies various types of accessories with an accuracy of 98.9% on average and a minimal user effort to construct a reference data set, which takes less than 30 seconds. Furthermore, we verify the robustness of MagID under diverse noisy conditions. One notable result is that MagID maintains high accuracy (an identification accuracy of 96.2% on average) without requiring additional reference data collection even when users moving around outdoor and indoor places. This is primarily thanks to the capability of MagID to extract noise-robust and environment-independent signatures for MagSafe accessories.

Our contributions can be summarized as follows:

- To the best of our knowledge, MagID is the first attempt to identify MagSafe accessories on commercial smartphones without requiring additional hardware on both accessories and smartphones. Based on this, MagID enables new interaction mechanisms to connect a smartphone's functionalities with accessories.
- We introduce an accessory identification technique that leverages not only magnetic but also non-magnetic signatures. Through extensive experiments, we show that this sensor-fused design allows MagID to achieve

high accuracy, robustness, and usability in various real-world environments.

II. RELATED WORKS

A. LARGE OBJECT CLASSIFICATION VIA MAGNETIC SENSING

Traditionally, there have been several attempts to leverage magnetic sensing to detect, identify, or examine large objects, such as vehicles [4], [5], [6], explosive remnants of war (ERW) [7], [8], and internal building structures (e.g., rebars). However, these works require high-precision sensing equipment to accurately identify or detect large ferromagnetic objects that distort their surrounding magnetic fields significantly. In contrast, our work aims to identify a relatively small objects, e.g., MagSafe wallets, using only a smartphone's built-in sensors without requiring additional or high-precision sensing devices.

B. MAGNETIC FINGERPRINTING FOR SMARTPHONES AND APPLICATIONS

Many studies have aimed to identify smartphones by analyzing variations of the magnetic field around the smartphones while using them [9], [10], [11]. Specifically, MagFingerprint [9] distinguishes smartphones by sensing how the magnetic field varies during charging with the use of magnetometer arrays. Baldini et al. [10] identify smartphones by applying stimuli through an external solenoid coil and observing the resulting magnetic response differences. That is, these methods need to use specialized hardware (e.g., magnetometer arrays and external solenoid coils) for smartphone identification, lowering its deployability. In contrast, Perez et al. [11] leverage a smartphone's built-in magnetometer for fingerprinting, but requiring intensive data collection, which takes several tens of minutes, for high accuracy.

Other works have proposed a method to recognize which application is currently running on smartphones [12], [13], [14]. They are mainly based on the observation that the electromagnetic field generated by mobile processors vary depending on the application usage. However, unlike our works to use sudden magnetic variations made during accessory attachment or detachment as a key feature for accessory identification, they rely on the long-term magnetic field variations for precise recognition of currently-running applications.

C. MAGNETIC-BASED INPUT INTERFACES FOR MOBILE DEVICES

Several efforts have been made to support new interaction mechanisms, which can widen an input vocabulary on mobile devices, based on magnetic sensing. For instance, some studies [15], [16], [17] have explored the feasibility of tracking finger movements through continuous localization of ring-shaped magnets, worn on a finger. Other studies aim to propose a new input interface with the use of various types/shapes of magnets around mobile devices [18], [19], [20], [21]. MagGetz [18] extends a smartphone's input space into the surroundings using magnet-equipped widgets such as joysticks, push buttons, and sliders. Cheung and Girouard [19] enable rotatory gesture input by tracking a magnet ring's orientation place near from smartphones. However, these interfaces are not designed for ubiquitous interaction scenarios where users are moving around.

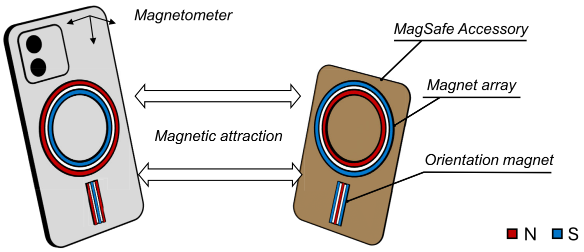


FIGURE 2. Magnetic attraction between a MagSafe-enabled smartphone and accessory.

III. PRELIMINARY STUDY

In this section, we explore the feasibility and challenges of identifying MagSafe accessories through magnetic sensing, a key enabler of MagID for supporting the functional connection of smartphones and accessories.

A. FEASIBILITY OF IDENTIFYING MAGNETIC ACCESSORIES

Starting with iPhone 12, Apple smartphones come with MagSafe technology. It allows users to securely attach accessories to the back of the smartphones, thus encouraging the emergence of a new class of smartphone accessories, such as fast wireless chargers, wallets, car mounts, coolers, and camera lenses.

The key underlying idea of MagSafe is to integrate magnets into smartphones and accessories. As shown in Fig. 2, both MagSafe-enabled smartphone and accessory have a circular array of magnets, called a MagSafe ring, in their mating surface. The two rings attract each other due to their opposite polarities [22], thus ensuring that the accessory snaps securely onto the smartphone. In addition, its circular shape allows the accessory to be attached to the smartphone in any orientation. Note that some accessories, such as wallets, require to be lined up correctly. It can be easily achieved by incorporating a straight-shape magnet, called an orientation magnet, into the accessories.

The magnet-embedded structure of MagSafe accessories leads to changes in the magnetic field around a smartphone when they are attached or detached. In particular, these magnetic variations are sensed using the smartphone's built-in magnetometer (see Fig. 3). Let $m(t)$ denote the magnetic signal value estimated at time t using the magnetometer. It is modeled as follows:

$$m(t) = s \cdot m^E(t) + b, \tag{1}$$

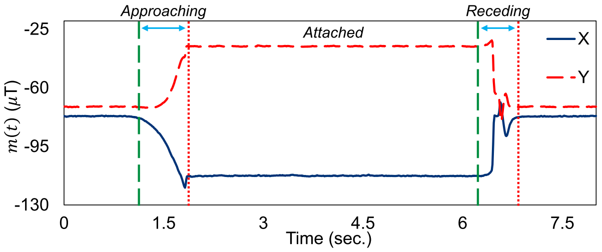


FIGURE 3. **Magnetic variations when using a MagSafe accessory. Note that in the entire feasibility study, we attached or detached MagSafe accessories to an iPhone 12 smartphone and measured how the magnetic field around the device varies using its built-in magnetometer with a sampling rate of 100 Hz.**

(a) In a charger (b) In a wallet (c) In a car mount

FIGURE 4. **Magnetic structure and strength of MagSafe rings over different accessories. Magnetic fields are measured using magnetic viewing film.**

where $m^E(t)$ denotes the Earth's magnetic field vector in the device's local frame at time t, s is a 3 by 3 matrix for soft-iron interference from magnetically-preamble objects, and b is a three-axis hard-iron bias caused by objects (e.g., permanent magnets) that produce a magnetic field. $m(t)$ first increases or decreases gradually as a MagSafe accessory approaches toward the smartphone for attachment. This is because the magnets in the accessory move closer to the smartphone, causing changes in the magnetic field bias (b) applied to the device. $m(t)$ then becomes stable once the accessory is securely attached to the smartphone and finally returns to the initial value after removing the accessory, i.e., when there is no hard-iron bias from the accessory.

The magnetic variations caused by MagSafe accessories can affect the operation of smartphone internal sensors, such as cameras. To ensure secure device management, Apple provides design guidelines for the accessories [22]. In particular, the guidelines specify that MagSafe rings integrated in accessories need to satisfy the dimension and polarity requirements. However, despite these guidelines, accessories are manufactured with magnets of slightly different shapes and strengths. For example, as shown in Fig. 4, a small gap exists in the magnet ring of a charger to connect a charging coil and circuit board. A magnetic wallet includes not only a magnet ring but also an orientation magnet for alignment. A car mount supports firm attachment of a smartphone even during driving by using strong magnets. Such a structural difference in the magnets of accessories makes the magnetic signal vary differently depending on the attached accessory as shown in Fig. 5. For example, attaching the car mount accessory causes a more significant change in the magnetic signal as it uses stronger magnets than others.

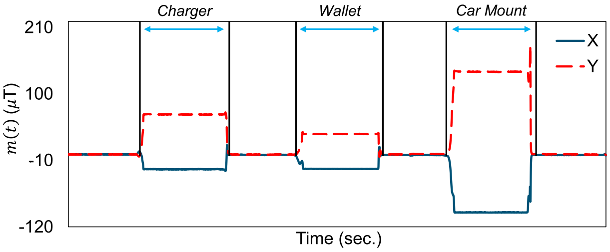


FIGURE 5. **Magnetic variations with different MagSafe accessories.**

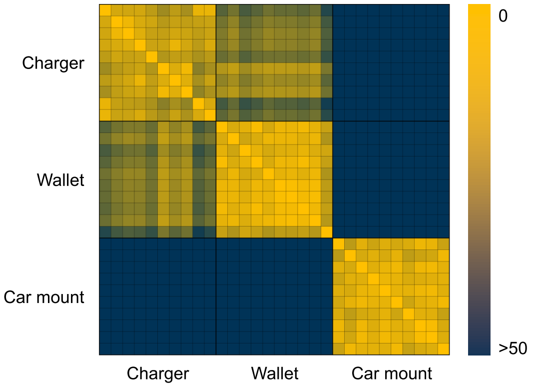


FIGURE 6. **Euclidean distance between magnetic signatures of MagSafe accessories. The magnetic signatures were obtained as the difference of *m(t)* before and after attaching accessories. Note that for each accessory, we collected its signature 10 times by repeatedly attaching and detaching it.**

In summary, when attaching and detaching a MagSafe accessory, the magnetic field around a smartphone varies *i*) noticeably and *ii*) differently depending on the accessory. This indicates that each accessory has a unique magnetic signature (see Fig. 6). Therefore, it is feasible to identify attached or detached accessories by analyzing magnetic signals collected from the smartphone's built-in magnetometer. It should also be noted that a MagSafe-enabled Apple smartphone involves two NFC chips. One is embedded in the center of the device and is used to identify MagSafe accessories equipped with an NFC tag. However, this NFC-based identification is allowed only for accessories officially licensed by Apple. Even if third party vendors integrates NFC tags into their accessories for identification, the functionality does not work. The other NFC chip, which is in the top of the smartphone, is used for general purposes. For example, by using it, we can read any NFC tags and communicate with other NFC-enabled devices. However, its communication range is too short to activate and read NFC tags involved in MagSafe accessories, which are attached to the center of the device.

B. CHALLENGES

However, there are still several challenges to be addressed in identifying accessories with magnetic signatures:

- *User movement-driven magnetic variations.* A magnetic signal $m(t)$ can vary due to not only magnetic accessories but also user movements. Suppose that a user is walking

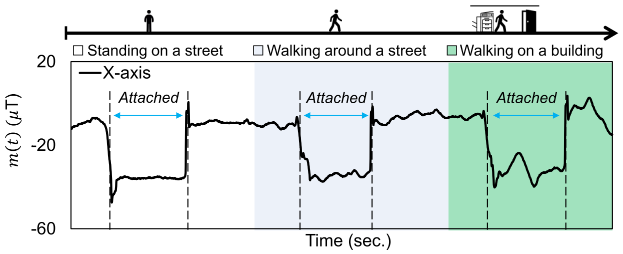


FIGURE 7. **Magnetic variations caused by user movements. The magnetic signals were collected by asking a participant to repeatedly attach and detach a Wallet accessory while walking around a street and a building.**

around while carrying a smartphone. The smartphone's orientation relative to the Earth's North pole will continuously change, and $m(t)$ fluctuates even without attaching an accessory (see Fig. 7). This noise can either falsely activate functions or applications in the absence of accessory attachment and distort an accessory's magnetic signature.

- *Unpredictable magnetic interference from surrounding environments.* Indoor environments, such as buildings, have local asymmetry of ferromagnetic and electromagnetic elements (e.g., walls, pillars, stairs, and electronic devices). This indicates that the magnetic interference from the surroundings varies unpredictably depending on the location in these environments. In other words, as shown in Fig. 7, an accessory's magnetic signature can be further distorted by changes in the magnetic interference.
- *Dependencies on attachment orientation.* As explained in Section III, the circular shape of a MagSafe ring supports attaching an accessory to a smartphone in any orientation. However, the magnet ring in some accessories, such as chargers, have non-identical structures (see Fig. 4(a)). For example, there is a small gap in the ring of the charger for placing charging coils. This irregular shape causes even the same accessory to have different magnetic signatures depending on its attachment orientation as demonstrated in Fig. 9.

IV. MagID DESIGN

Fig. 8 illustrates the overall procedure of MagID that *i*) identifies MagSafe accessories attached to or detached from a smartphone and *ii*) activates functions or applications mapped to the identified accessories. Specifically, we address the challenges discussed in Section III-B with our novel design for identifying accessories. First, it continuously collects both magnetic signals and magnetic noise-tolerant data using a smartphone's built-in sensors, including magnetometers, accelerometers, and gyroscopes. We collaboratively use them to cancel noise out from the magnetic signals and to pinpoint when an accessory event (attachment or detachment) occurs. Once detected, we extract two key features, including the accessory's magnetic signature and the smartphone's battery state, and use them to construct a reference data set (in a registration phase) or to identify the accessory (in an interaction phase). Note that we support precise identification regardless of the attachment orientation of accessories by providing users with straightforward guidance to collect the reference set under various orientation conditions.

A. SENSOR-FUSED MAGNETIC NOISE CANCELLATION

One major goal in designing MagID is to identify MagSafe accessories with high accuracy, while avoiding false identification results caused by magnetic noise. In other words, it is essential to discard the noise from a magnetic signal for precise accessory identification. Let $m(t_i)$ denote a three-axis magnetic field vector collected at the i-th sample time instant using a smartphone's magnetometer. We first minimize the effect of magnetic interference from the surrounding environments by calibrating $m(t_i)$ using magnetic interference parameters s and b as follows:

$$m^C(t_i) = s^{-1}(m(t_i) - b). \tag{2}$$

Note that the interference parameters are obtained and periodically updated in two ways. First, we use calibrated magnetometer readings provided by commercial mobile platforms, including iOS and Android [23], [24], which support automatic calibration of the magnetometer. Also, whenever any accessory event is detected, we estimate how much the magnetic field around the smartphone varies due to the event and update the hard-iron interference bias b based on the estimation results.

However, as explained in Section III-B, the magnetic signal can further vary due to user movements that cause changes in the device's orientation. Therefore, we discard device orientation-dependent components, i.e., the user movement-driven noise, from $m^C(t_i)$, especially by using gyroscope readings. Suppose that $w(t_i)$ is a three-axis gyroscope reading collected at a sample time instant t_i. Using $w(t_i)$, we first compute $\Delta q(t_{i-1}, t_i)$, a quaternion to represent a rotation change of the smartphone's local frame between t_{i-1} and t_i [25]. We finally obtain an orientation-independent magnetic field vector ($m^R(t_i)$) as follows:

$$\begin{aligned} m^R(t_i) &= m^R(t_{i-1}) + \Delta m^R(t_i) \\ &= m^R(t_{i-1}) + (m^C(t_i) \\ &\quad - \Delta q^{-1}(t_{i-1}, t_i) \cdot m^C(t_{i-1}) \cdot \Delta q(t_{i-1}, t_i)). \end{aligned} \tag{3}$$

B. ACCESSORY SIGNATURE EXTRACTION

Once m_i^R is obtained, MagID leverages it as a key feature for enhancing robustness in the remainder of the identification process, especially in detecting accessory events and extracting signatures.

1) ACCESSORY EVENT DETECTION WITH ACCELEROMETERS

We design a detection method based on our observation that a magnetic signal suddenly varies in the presence of accessory events (see Fig. 3). Specifically, MagID first extracts high-frequency components $m^H(t_i)$ from $m^R(t_i)$ by applying a Butterworth high-pass filter with an order of

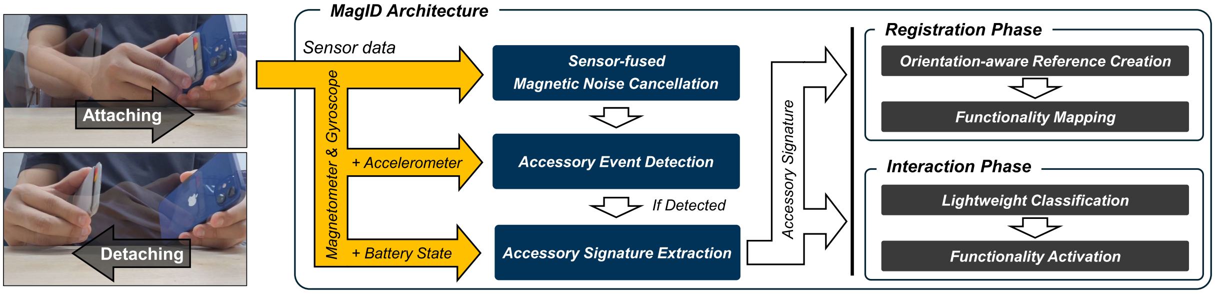


FIGURE 8. Overview of MagID.

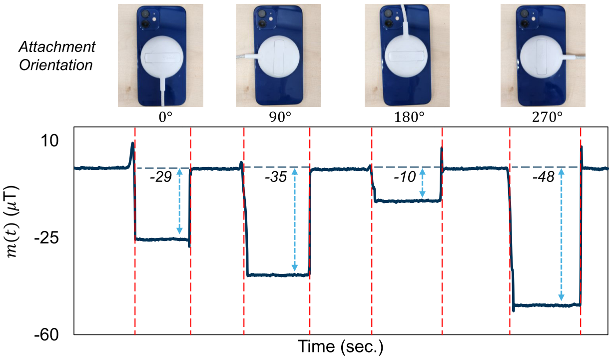


FIGURE 9. Dependency of magnetic signatures on an accessory's attachment orientation.

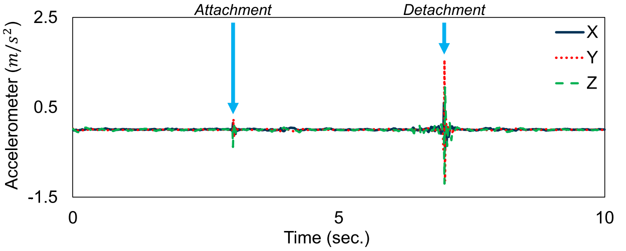


FIGURE 10. Variations in accelerometer readings when a MagSafe accessory event is occurred.

4 and a cutoff frequency of 10 Hz. We then attempt to further increase the robustness of detecting accessory events by using accelerometer readings together. Interestingly, accessory events also produce transient changes in the accelerometer readings (see Fig. 10). This is because when attaching an accessory to a smartphone, a sudden collision between them happens as their magnets strongly attract each other. In addition, users need to exert a physical force to detach the accessory from the smartphone. Motivated by this observation, we extract $a^H(t_i)$, a three-axis acceleration vector at a sample time instant t_i filtered by a Butterworth high-pass filter with an order of 4 and a cutoff frequency of 40 Hz. Note that this high-pass filter design is based on the observations on the frequency characteristics of acceleration signals during common daily activities, such as walking, jogging, and taking transportation [26]. We then detect the occurrence of an accessory event at t_i if $|m^H(t_i)|$ and $|a^H(t_i)|$ exceed a detection threshold ϵ^M and ϵ^A, respectively, i.e., if both features suddenly vary. Note that ϵ^M and ϵ^A are empirically set to 1.0 and 0.01.

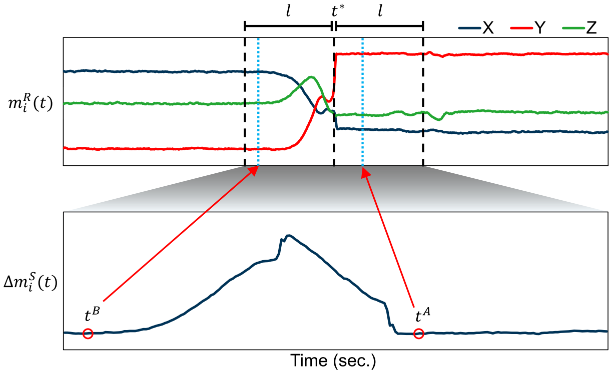


FIGURE 11. Procedures to find magnetically stable points.

2) PRECISE MAGNETIC SIGNATURE EXTRACTION

After detecting an accessory event, MagID extracts the accessory's magnetic signature by estimating how much $m^R(t_i)$ varies due to the event. However, as observed in Section III, the magnetic signal changes not only at the moment when the event occurs but also when the accessory moves toward (or away from) the smartphone for attachment (or detachment). So, to precisely extract the signature, we first find two time instants; one when the accessory is securely attached to the smartphone and the other when the accessory has enough distance from the smartphone not to affect the magnetic field around the device. In other words, we detect when the magnetic signal remains stable before and after the accessory event, as demonstrated in Fig. 11. Suppose that an accessory event is detected at t^*. MagID first computes the moving average of the magnitude of $\Delta m^R(t_i)$ ($m^R(t_i) - m^R(t_{i-1})$) around t^*, which indicates the stability of the magnetic field during the event, as follows:

$$m^S(t_i) = \frac{\sum_{j=i}^{i+n^S} |\Delta m^R(t_j)|}{n^S}, \tag{4}$$

where n^S is the number of windowing samples, which is set to 40, t_i ranges from $t^* - l$ to $t^* + l$, and l is a duration of 1 second. We then compute two time instants t^B and t^A using $m^S(t_i)$ as the time when $m^S(t_i)$ reaches minimum before and after t^*, respectively. Once t^B and t^A are obtained, MagID finally extracts the accessory's signature, denoted as m^E, while minimizing the distortion caused by user movements and environmental changes:

$$m^E = m^R(t^A) - \Delta q^{-1}(t^B, t^A) \cdot m^C(t^B) \cdot \Delta q(t^B, t^A)). \quad (5)$$

Note that for more precise identification, we also collect how the smartphone's battery state changes after the accessory event and use the state, such as a discharging or charging state, as an additional signature.

C. ACCESSORY IDENTIFICATION

Using both magnetic and non-magnetic signatures, we create a reference set (in the registration phase) or identify the accessory (in the interaction phase).

1) ATTACHMENT ORIENTATION-AWARE REFERENCE CREATION

Before using a new MagSafe accessory, we collect a set of reference data for the accessory by asking a user to attach and detach it multiple times (e.g., 5 – 10 times) and taking its magnetic signature and battery state for each attachment event. Specifically, the collected data are then paired with the accessory's id and included in the reference set. It should be noted that, as discussed in Section III-B, some accessories can be attached to any orientation, and their signature becomes different depending on the orientation. In other words, for these accessories, it is required to construct their template data under various orientation conditions. We easily achieve this with a simple instruction that requests a user to attach an accessory and rotate it by 360 degrees. Suppose that after attaching the accessory, its signature (m^E) is obtained using (5). MagID then keeps t^A used for the extraction and measures its orientation-dependent signatures for all time instants after t^A, i.e., during the rotation, as

$$m^E + m^R(t) - \Delta q^{-1}(t^A, t) \cdot m^C(t^A) \cdot \Delta q(t^A, t)). \quad (6)$$

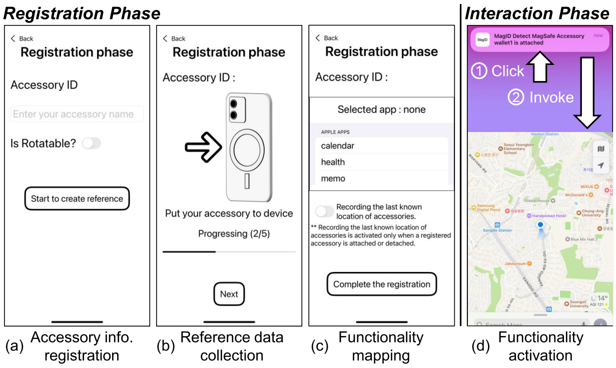
Once a set of reference data is constructed for a specific accessory, we do not request additional reference data collection under the assumption that the accessory's signatures remain constant.

2) LIGHTWEIGHT ACCESSORY CLASSIFICATION

When an accessory event occurs, MagID identifies the accessory by comparing its signatures with reference data collected in the registration phase. Let m^E and c denote the magnetic signature and battery state obtained after the event. MagID first takes a subset of reference data that has the same battery state signature as c. We then find the index of the reference (i^*) that has the most similar signature with m^E among the selected reference data as follows:

$$i^* = arg \min_{i=1}^{n^R} |m^E - m_i^R|, \quad (7)$$

where n^R is the number of the selected references and m_i^R is each reference's magnetic signature. Finally, we classify the accessory as acc_{i^*}, the most similar reference's accessory id, and activate its mapped function or application. It is noteworthy that this accessory classification process is done only for attachment events. If a new event is detected when acc_i is attached to a smartphone, i.e., in the occurrence of a detachment event for acc_i, MagID simply activates functionalities mapped to the detachment event of acc_i (if exists) without additional classification.



Put your accessory to device

Progressing (2/5)

Recording the last known location of accessories.

** Recording the last known location of accessories is activated only when a registered accessory is attached or detached.

MagID Detect MagSafe Accessory wallet1 is attached

(a) Accessory info. registration (b) Reference data collection (c) Functionality mapping (d) Functionality activation

FIGURE 12. Preview of a MagID prototype implementation.

V. IMPLEMENTATION

We implement a prototype of MagID as an application running on iOS 17.0 or above. It continuously collects accelerometer, gyroscope, and magnetometer readings with a sampling rate of 100 Hz. In particular, to discard environmental noise in the magnetometer readings, we use the `CMCalibratedMagneticField` [27] structure that offers magnetometer field data calibrated by iOS. The application then leverages the collected data to identify accessories, as explained in Section IV and finally activates their corresponding functionalities.

Fig. 12 illustrates graphical user interfaces to support functionality activation. In the registration phase (see Fig. 12(a–c)), a user is first asked to register an accessory with its properties, such as name and rotatability. The application then collects the accessory's reference magnetic signatures by requesting the user to simply attach and detach the accessory (if the accessory is not rotatable) or to rotate the accessory after attachment (otherwise). Finally, the user maps a specific functionality to the accessory as desired (see Fig. 12(b–c)). Note that the user can also change the mapping information and even discard the registered accessory if it is not in use. After the registration, i.e., in the interaction phase, the application runs in the background while waiting for accessory events. Once an event occurs, it identifies the attached or detached accessory and activates the functionality mapped with the accessory (see Fig. 12(d)). Specifically, our prototype implementation supports the following two types of functionalities:

- *Invoking applications.* When an accessory is attached, MagID automatically launches its mapped application. Towards this, as shown in Fig. 12(d), it sends a push

FIGURE 13. MagSafe accessories used in our experiments. Please refer to Table 1 to see each accessory's properties.

TABLE 1. Properties of MagSafe accessories.

	Usage	MFM	Charger	Rotatable	Portable
B1	Power bank	N	Y	N	Y
C1	Charger	N	Y	Y	N
C2	Charger	N	Y	Y	N
C3	Charger	Y	Y	Y	N
L1	External cooler	N	N	Y	N
G1	Ring holder	N	N	Y	Y
G2	Ring holder	N	N	Y	Y
M1	Car phone holder	N	Y	N	N
M2	Charging stand	N	Y	Y	N
M3	Mount	N	N	Y	N
W1	Wallet	N	N	N	Y
W2	Wallet	N	N	N	Y
W3	Wallet	N	N	N	Y
W4	Wallet	Y	N	N	Y

MFM is the abbreviation of "Made For MagSafe ", which indicates an accessory licensed by Apple.

notification to a user once an accessory is attached and invokes the application when the user clicks the notification. We use such a notification-based application activation method since iOS prohibits background-running applications, such as the MagID application, to directly launch other applications without user consent.

- *Recording the last known location of accessories.* MagID continuously records when and where accessories are attached and detached. This information is then used for various purposes, e.g., to find lost accessories (see Fig. 1).

VI. EVALUATION

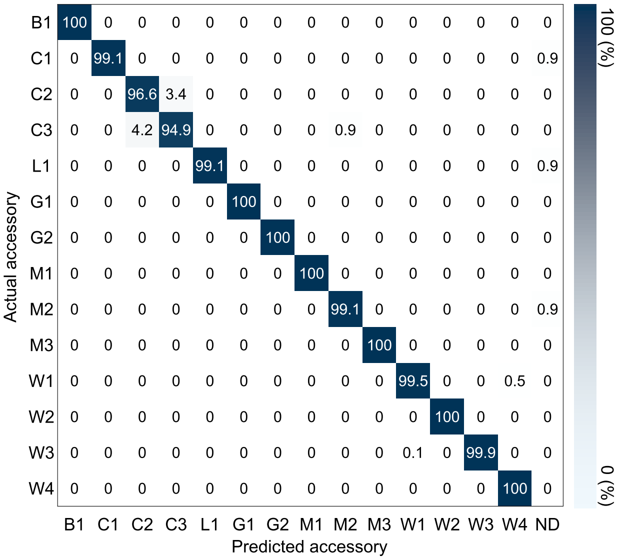
In this section, we first evaluate the overall performance of MagID and verify its robustness across various real-world environments.

A. EVALUATION SETUP AND METHODOLOGY

We conducted experiments with a single user using an iPhone 12 smartphone, the first MagSafe-enabled device, and 14 MagSafe accessories, each of which has different shapes and properties, as shown in Fig. 13 and Table 1. The user repeatedly attached and detached the accessories to the smartphone while sitting on a chair in a classroom, i.e., with virtually no fluctuations in ambient magnetic noise. At the same time, we collected sensor data using the smartphone's built-in magnetometer, gyroscope, and accelerometer with a sampling rate of 100 Hz. More specifically, the data collection was performed in the following steps: *i*) the smartphone is initially placed on a desk, *ii*) the user lifts the phone to attach the accessory, *iii*) the user attaches the accessory to the back of the smartphone, *iv*) the accessory is detached after a while (e.g., 5 seconds after the attachment), and *v*) the user put the smartphone on the desk. This process was repeated 50 times for each accessory. We then verified the performance of MagID via 10-fold cross validation, which uses the data collected from five among the 50 trials as the reference data and the others as the test data. Unless otherwise specified, all experiments followed this standard setup.

Metrics. We use the following two metrics to evaluate the performance of MagID :

- *Identification accuracy.* It is defined as the probability of successful accessory identification. That is, we compute the identification accuracy as $\frac{n^I}{n^O}$, where n^I is the number of successfully detected and identified accessory events, and n^O is the total number of occurrences of accessory events.
- *False activation rate (FAR).* As explained in Section III-B, MagID might falsely activate functions or applications due to magnetic noise, resulting in severe degradation of user experience. So, we also measure the frequency of false activations while using MagID, i.e., FAR, as $\frac{n^F}{n^O}$, where n^F is the number of false activation occurrences during data collection.



	B1	C1	C2	C3	L1	G1	G2	M1	M2	M3	W1	W2	W3	W4	ND
B1	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	99.1	0	0	0	0	0	0	0	0	0	0	0	0	0.9
C2	0	0	96.6	3.4	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	4.2	94.9	0	0	0	0	0.9	0	0	0	0	0	0
L1	0	0	0	0	99.1	0	0	0	0	0	0	0	0	0	0.9
G1	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0
G2	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0
M1	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0
M2	0	0	0	0	0	0	0	0	99.1	0	0	0	0	0	0.9
M3	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0
W1	0	0	0	0	0	0	0	0	0	0	99.5	0	0	0.5	0
W2	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0
W3	0	0	0	0	0	0	0	0	0	0	0.1	0	99.9	0	0
W4	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0

FIGURE 14. Confusion matrix of overall identification for each accessory. 'ND' denotes accessory events not detected by MagID. That is, the mean of 'ND' fields is equal to an average detection error rate of MagID.

B. OVERALL PERFORMANCE OF MagID

Fig. 14 shows that MagID can identify a variety of MagSafe accessories with high accuracy (99.2% on average).

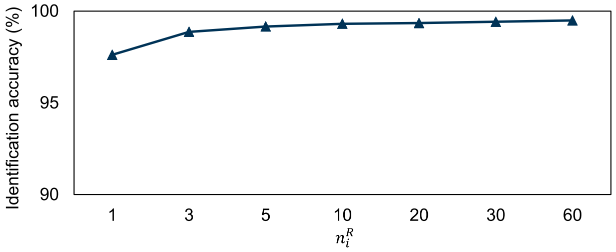


FIGURE 15. **Impact of reference data set size. Note that n_i^R denotes the number of reference data for each accessory.**

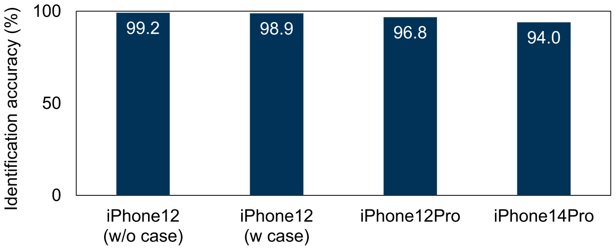


FIGURE 16. **Identification accuracy on different device. Note that we also measured the effect of an additional MagSafe case with an iPhone 12 smartphone.**

In particular, it successfully detects most accessory events with an average detection error rate of 0.2% and without false activation. This is because we minimize the effects of user movements and environmental magnetic noise in detecting accessory events by collaboratively using magnetometer, gyroscope, and accelerometer readings. The identification accuracy slightly drops with some accessories (e.g., C2 and C3) as they involve magnets with similar structures. However, most accessories (except them) have different magnetic characteristics, allowing MagID to precisely distinguish them using their unique magnetic signatures. The accuracy can be further improved in real-world scenarios where users have a few number of smartphone accessories. For example, under the assumption that one of each type of accessory is used (i.e., a total of 6 accessories are used), MagID achieves an identification accuracy of 99.7%.

1) IMPACT OF THE SIZE OF REFERENCE DATA SET

As described in Section IV-C, MagID constructs a set of reference data in the registration phase by asking users to attach and detach accessories multiple times. Whereas requiring more reference data may help increase identification accuracy, it can compromise usability due to increased user efforts. Therefore, we measured the performance of MagID while changing the number of reference data for each accessory, as shown in Fig. 15. Even with a small number of reference data (e.g., $n_i^R = 1$), it achieves a high identification accuracy (97.6% on average). The accuracy increases up to 99.2% as n_i^R increases to 5 since MagID can get more diverse signatures for accessories. A further increase in n_i^R also improves the accuracy, but only slightly. Therefore, we set the default value of n_i^R to 5, which requires users only 30 seconds to register accessories.

TABLE 2. **Elapsed time of MagID for accessory identification (Unit = milliseconds).**

	Noise cancellation & Detection	Signature-extraction	Class-ification	Total
Elapsed Time	4.61	1502.95	0.35	1503.30

2) DEPLOYABILITY OF MagID

We conducted experiments to verify that MagID can work well on various smartphones with different form factors. As demonstrated in Fig. 16, MagID can provide a high accuracy of more than 94% regardless of the smartphone form factors and even in the presence of additional magnetic cases. This is thanks to MagID's capability to extract magnetic signatures dependently on accessories, not devices. From this result, we believe that MagID can be deployed on any MagSafe-enabled smartphones, including recent iPhone models and diverse future mobile devices with a new wireless charging technology (Qi2).

3) RESPONSIVENESS OF MagID

We investigate how quickly MagID can activate functionalities in the occurrence of accessory events. Towards this, we measured an average elapsed time for each processing step by attaching and detaching an accessory 1,000 times. Table 2 shows that MagID requires 1.5 seconds in total to identify accessories. Notably, most processing steps (except signature extraction) takes less than 5 ms as MagID leverages *i*) low-dimensional feature vectors and *ii*) computationally-lightweight algorithms in detecting and classifying accessory events. However, it consumes more than 1.5 seconds in extracting signatures. This is primarily because it is possible to get the smartphone's batter state precisely approximately 1.5 seconds after attaching or detaching an accessory.

4) BATTERY CONSUMPTION OF MagID

We conducted experiments to evaluate how MagID affects the battery life of smartphones. In particular, we implemented the prototype of MagID on Android since it provides more detailed information about battery usage. We then run the MagID prototype, which continuously collects and analyzes sensor data, on a Google Pixel 4 for a total of 100 minutes while measuring the energy consumed using PowDroid [28]. Note that during the entire experiments, we set the smartphone's screen brightness levels consistently. The results show that running MagID increases total battery usage by 1.5 mAh over time compared to the idle case where MagID is not used. That is, MagID has a negligible impact on battery life thanks to its use of low-power sensors and low-complexity processing techniques.

C. ROBUSTNESS OF MagID

We conducted additional experiments to evaluate the robustness of MagID under various conditions, including the presence of electronic and magnetic objects, user movements,

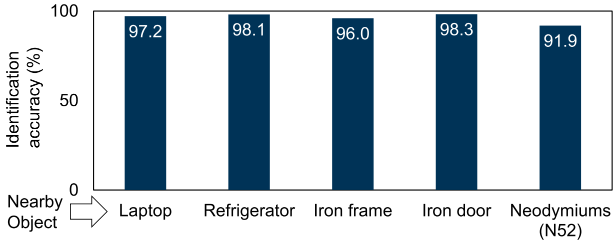


FIGURE 17. **Identification accuracy when electronic or magnetic objects are placed close to (within 1 meter) a user. Note that in the 'laptop' case, we ran the CPU of a laptop at around 100% utilization to generate a strong electromagnetic field.**

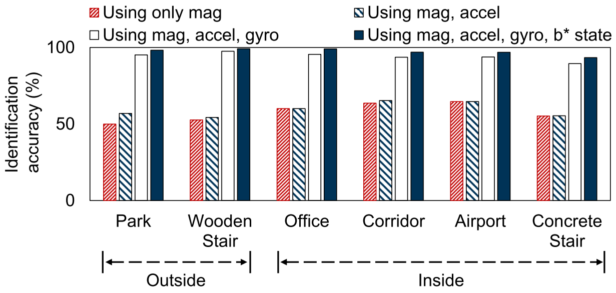


FIGURE 18. **Identification accuracy in diverse noisy environments while walking. In the legend, 'accel' represents an accelerometer, 'gyro' represents an gyroscope, 'mag' represents a magnetometer, 'b* state' represents a battery state.**

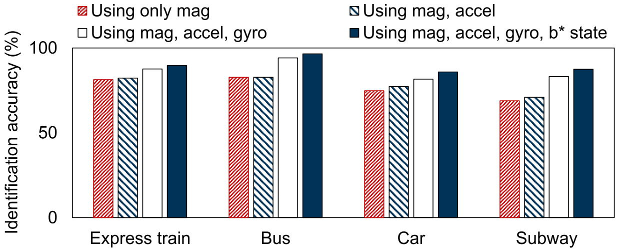


FIGURE 19. **Identification accuracy while taking transportation.**

dynamic environmental changes, temporal variations, and attachment orientations. Specifically, we collected additional data sets for each experiment with a single user as follows:

- *Magnetic object data set.* We collected data in the same manner as described in the default setup in Section VI-A, but in five different indoor environments, each with different electronic or magnetic objects, such as a laptop, a refrigerator, an iron frame, an iron door, and neodymium magnets, placed in front of the user.
- *User movement & environmental change data set.* We asked the user to *i*) move around outdoor and indoor places and *ii*) take transportation (e.g., buses and trains). During this time, the user naturally carried a smartphone and portable accessories (see Table 1) and attached/detached the accessories repeatedly (30 times for each accessory). In particular, in the transportation scenarios, the user sat in a seat during the experiment.
- *Temporal variation data set.* Over six months, we repeatedly collected data with MagSafe accessories in the same manner as described in the default setup in Section VI-A.
- *Attachment orientation data set.* For each rotatable accessory (listed in Table 1), we collected additional data with the user by performing the attachment and detachment of the accessory 60 times while changing the attachment orientation at each trial.

It should be noted that, unless otherwise stated, all the data were collected on the same day with our default setup in a classroom while the user is sitting in a chair. In addition, in the entire robustness test, we used these data sets as a test data set and the data set collected in the default environment as a reference data set.

1) AGAINST THE PRESENCE OF ELECTRONIC AND MAGNETIC OBJECTS

As explained in Section III-B, magnetic signals are also affected by electromagnetic elements. Fig. 17 illustrates the effect of these electronic and magnetic objects on the performance of MagID. Notably, neodymium magnets, which produce a strong magnetic field, make MagID suffer from low accuracy, e.g., 91.9%, because the magnetic field from the magnets severely distorts accessories' magnetic signatures. However, except for extreme case, which is not common in the real world, MagID achieves a reasonable level of identification accuracy (97.4% on average) when there exists daily electronic and magnetic objects.

2) AGAINST USER MOVEMENT AND DISPLACEMENT

As explained in Section III-B, magnetic signals can also vary due to user movements, i.e., changes in a smartphone's orientation relative to the Earth's magnetic field. Even worse, such magnetic variations become much more severe when moving around indoor environments that have local asymmetry of ferromagnetic and electromagnetic elements. Thus, these variations distort accessories' magnetic signals, resulting in a significant drop in identification accuracy when using only magnetometers to detect and identify accessory events as shown in Fig. 18. However, MagID effectively mitigates the effect of the movement in magnetic noise by using non-magnetic features, such as gyroscope readings, high-pass filtered accelerations, and battery states, together. For example, Fig. 18 shows that when walking around indoor and outdoor environments, using both the magnetometer and accelerometer for accessory identification increases average identification accuracy by 1.8% points compared to the case of using the magnetometer alone. In addition, MagID achieves a significant improvement in accuracy (by 34.8% points on average) with the use of the gyroscope, which can effectively cancel out user movement noise in the magnetic signals. Furthermore, MagID achieves a further improvement by using battery status as an additional identification feature.

Notably, MagID experiences performance degradation when taking transportation (see Fig. 19). This is because the surrounding magnetic environment changes suddenly and

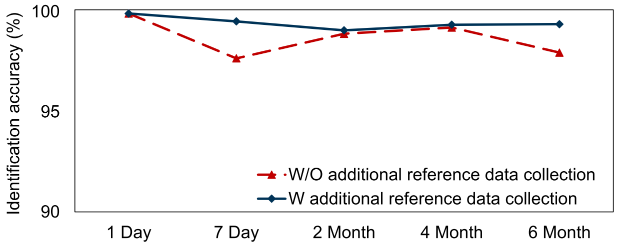


FIGURE 20. **Robustness of MagID under temporal variations.**

unpredictably due to the high speed of movement (in the case of train and car) and the sophisticated underground structures (in the case of subway). Nevertheless, compared to using only magnetic features, the sensor fusion design of MagID enables to achieve a reasonable level of identification accuracy (89.9%) and FAR (2.0%) on average. In addition, in other public transportation, such as buses that move at slower speeds, MagID can provide an accuracy of 96.5%, indicating that it provides sufficiently acceptable accuracy in many daily situations, except in cases involving high-speed movement and extremely noisy environments (e.g., tunnels and elevators).

3) AGAINST TEMPORAL VARIATIONS

Fig. 20 illustrates that once accessories are registered, MagID can accurately identify them using the reference data collected previously. For example, MagID maintains a high level of identification accuracy (98.0%) even six months after registration. This indicates that for a specific accessory, its signatures remain virtually constant, allowing MagID to avoid additional reference data collection. That is, reference data collection is required only once at a registration phase, thereby preventing a decrease in usability.

4) AGAINST ATTACHMENT ORIENTATIONS

As mentioned in Section IV-C, MagID collects additional reference data by rotating accessories if they can be attached in any orientations. Note that this simple orientation-aware data collection takes approximately less than 30 seconds. Table 3 shows the effectiveness of this attachment orientation-aware reference collection in identifying rotatable accessories. If we construct a set of reference data without considering attachment orientations, MagID fails to accurately identify accessories with an accuracy of 85.3%. Conversely, using the orientation-aware collection method increases the diversity of magnetic signatures in the reference data set and thereby improves the performance of MagID by 10.7% points. Note that the accuracy of 96.0% is relatively low compared to previous results. This is primarily because some rotatable accessories (e.g., C1 and M2) have similar magnetic signatures with others at certain attachment orientations. However, as discussed in Section VI-B, this problem can be alleviated in real-world scenarios where users employ fewer accessories, e.g., one of each type of accessory.

TABLE 3. **Effect of attachment orientation-aware reference collection.**

	W/o attachment orientation-aware	W attachment orientation-aware
Identification accuracy	85.3%	96.0%

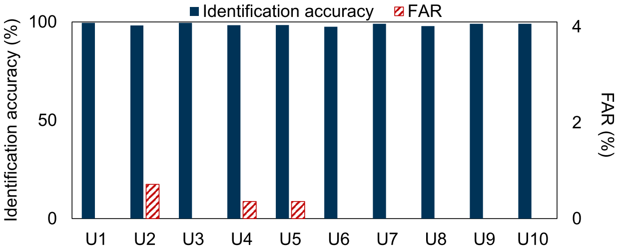


FIGURE 21. **Performance of MagID with real-world users.**

D. USER STUDY

We further verified the performance of MagID with real-world users. To this end, we recruited 10 users from our university and asked them to attach and detach accessories repeatedly (10 times for each accessory). Other experimental settings are the same as those of the default setup. Fig. 21 shows that MagID achieves a high degree of identification accuracy (98.7% on average) with a low false activation rate of 0.1% on average. This is because MagID effectively discards user movement-driven noise from magnetic signals and eventually extracts accessory-dependent but not user-dependent magnetic signatures. Note that some users (e.g., U2, U4, and U5), who are not familiar with using MagSafe accessories, have struggled to attach and detach accessories, causing undesired and severe magnetic fluctuations even before and after accessory events. However, even in those cases, MagID successfully prevents the occurrence of false activation events with a FAR of lower than 0.8%.

VII. DISCUSSION

As referred in Section III, we observed that different types of accessories have non-identical form factors and involve magnets with different shapes and strengths, making them to have unique magnetic signatures. In addition, through experiments, we also confirmed that even the same type of accessories, e.g., chargers, which have similar form factors, can be precisely distinguished. However, as the number of MagSafe accessories a user utilizes increases gradually, the probability of having similar magnetic signatures between different accessories may also increase, causing performance degradation in MagID. To address this, our future work includes to further increase the modalities of accessory signatures and fuse these different types of features to enable more precise accessory identification. For example, we can leverage collision sounds generated when attaching an accessory to a smartphone as an additional non-magnetic signature.

Another discussion point is that despite the high identification accuracy and low FAR of MagID, it can be malfunctioned sometimes. For example, it may incorrectly identify attached accessories or detect accessory events due to magnetic noise. Then, undesired applications or functions will be invoked, resulting in a severe decrease in usability. One possible solution is to provide push notifications or toasts with shortcuts to invoke applications or functions, instead of directly invoking them without user consent when an accessory event is detected. Furthermore, we believe that as mentioned above, by further improving the accuracy of MagID through sensor fusion, we can reduce the occurrence of malfunctions and thus enhance usability.

VIII. CONCLUSION

In this paper, we propose MagID, a novel framework that supports a functional connection between smartphones and MagSafe accessories. A key enabler of MagID is to identify accessories when they are attached to or detached from smartphones through magnetic sensing. In particular, to improve the noise robustness of MagID, we collaboratively leverage various types of sensor data, including magnetometer, accelerometer, gyroscope, and battery state readings, each of which can be obtained from most commercial smartphones. Once an accessory is identified, MagID then triggers applications or functions mapped with the accessory. We evaluated the performance of MagID by conducting extensive experiments with a prototype of MagID, implemented as a standalone iOS application. Our evaluation results demonstrated that MagID can achieve an average identification accuracy of 99.2% in ideal environments with minimal registration effort and maintain the high accuracy even over six months without requiring additional reference data collection. Furthermore, robustness tests conducted in environments with various noise sources showed that MagID can provide sufficient convenience to users even in diverse conditions. We believe that in the near future, MagID will be adopted not only in the iPhone, but also in a wider range of smartphones as they come with the next-generation Qi2 wireless charging standard, which incorporates MagSafe.

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