Low-cost and Non-visual Labels Using Magnetic Printing

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This paper presents MagCode, a new type of barcode. MagCode label is printed with magnetic ink through ordinary printers and stores data in the magnetic field. By swiping a magnetometer over it, the stored data can be extracted. Thus, unlike ordinary barcodes, MagCode does not rely on visual channels to decode, implying untapped interaction opportunities when decoding ordinary visual code is not preferred or not possible. Its application cases include an unobstructed and low-cost input interface for wearables, whose visual sensing capabilities are usually limited. Further, MagCode's patterns can be designed to be visually-undecodable, and our evaluation shows that accessing its magnetic signal requires very close approximation. These properties allow for using MagCode labels to convey covert and sensitive information, such as Easter eggs in games and payment credentials in daily life.

CCS Concepts: • **Human-centered computing → Interaction devices**; • **Hardware → Tactile and hand-based interfaces**; Sensor devices and platforms.

Additional Key Words and Phrases: Fabrication, Input Techniques, Artifact or System

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1 INTRODUCTION

Machine-readable labels are essential items to make the physical world more perceivable and understandable by computers. Two types of labels, RFID tags using radio technology and barcodes based on visual sensing, are widely used in everyday life [23, 34]. Compared with RFID tags, barcodes are featured by its low fabrication and consumption overhead. They are printable on ordinary papers, and readable through visual sensors, *e.g.*, smartphone cameras.

However, barcodes convey information through visual patterns, which leads to several shortcomings in practice. First, the decoding device must have visual sensors, which disallows its usage in light-weight computing devices such as wearables. Further, barcodes are primarily designed to please vision algorithms. Their visual patterns consist of binary and distinct blocks and are not quite consumable for humans. The negative impact of their visual appearance on the surroundings has prevented them from being adopted in cases where a consistent aesthetic is preferred [16].

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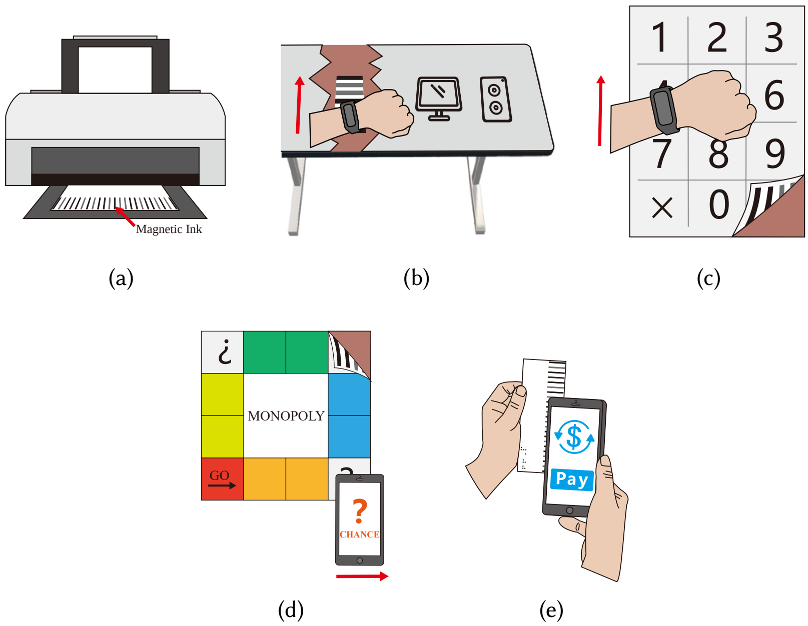


Fig. 1. **Concept of Fabricating and Using MagCode Labels**. (a) MagCode can be printed on normal papers with ordinary printers. (b) Swiping the device, *e.g.*, wristband, over the MagCode label to reveal the stored data. (c) An array of MagCode labels actualize A paper keyboard for the wristband. (d) Combining MagCode with tabletop games, such as using it as a label to trigger hidden events. (e) A MagCode label conveying account credentials is used for offline payment.

Moreover, the dependence on the visual channel also exposes barcodes to a relatively open environment. Without proper covering, anyone nearby can capture its content. This leads to many risks when trying to leverage barcodes to store sensitive information such as payment credentials [12].

This paper presents MagCode, a new form of barcode that preserves the low-cost property but is free of the above insufficiency. Like ordinary barcodes, MagCode is printable by printers, but it does not rely on visual channel to decode. Its content generates magnetic signals and can be sensed with a digital compass or magnetometer, which are ubiquitous sensors in light-weight digital devices like wearables. This allows for new interaction opportunities for these devices lacking convenient input methods. Moreover, MagCode can be entirely invisible, and hence it is not visually offensive and can be hidden from visual sniffers.

MagCode is inspired by the Magnetic Ink Character Recognition (MICR). MICR uses the magnetic ink to fabricate machine-readable content in the era that lacks robust visual decoding capabilities. MICR has been used in bank systems for decades. The key idea of MagCode is to use the MICR magnetic inks to print and generate magnetic signals to carry information. As shown in Figure 1(a), since the magnetic inks are widely used for manual check printing at home, MagCode labels are printable through daily consumer printers [6]. MagCode uses evenly-spaced black-white stripe lines to represent information. Bits are encoded by varying the intensity of the black strip lines. As shown in Figure 1(b)(c)(d)(e), its content can be decoded through swiping the mobile device over the printed area.

Since MagCode does not convey information through the visual channel, it can be hidden and decorated by the surface over it. Figure 1(b) demonstrates the application of labeling daily items for smart home control without affecting the visual aesthetic. Figure 1(c) shows a printed keyboard based on multiple MagCode labels. This renders a convenient input interface for the wristband. Further, MagCode can be used as game props shown in Figure 1(d), extending the interaction mode of tabletop games. Moreover, MagCode can be designed to avoid leaking information visually. We develop an offline digital payment system shown in Figure 1(e) to demonstrate its security advantages.

This paper contributes to the design and fabrication of a novel labeling technology based on magnetic printing. It is complementary to existing visual barcodes and has advantages for wearable interaction and security applications. In the following sections, we first introduce the background and related work in §2. An overview of fabricating and using MagCode labels is described in §4. §3 describes the implementation details of MagCode. The aforementioned applications are elaborated in §5.

2 BACKGROUND AND RELATED WORK

MagCode is inspired by magnetic storage and related to interactive technologies based on magnetism. The applications based on MagCode are related to designed barcodes, wearable devices, and the security issues in digital payment.

2.1 Magnetic Storage

MagCode stores data via magnetic materials. This subsection reviews closely related magnetic storage techniques.

MICR [2, 3] has been used in bank systems for decades. The primary goal of MICR is to enable auto-processing of checks by recognizing printed characters. While OCR (Optical Character Recognition) can be used for the same purpose, MICR tends to have lower cost and higher accuracy at the time when it was invented [26]. The approach of MICR is to print characters with ink containing magnetizable particles, or magnetic ink. To recognize the characters, the check is passed through a MICR reader, which magnetizes the printed content and records the intensity of the magnetic field. Since the font of the characters is intentionally shaped, the corresponding magnetic waveforms are unique and helpful in filtering out the background and noise [25].

MagCode is motivated by MICR in using magnetic ink to print. However, they are different in other aspects. First, MICR characters are also human-readable, while MagCode is not. Second, MICR reader is different from magnetometer in mobile devices. MICR reader has a very narrow sensing area and only captures the dynamics of the magnetic field, which prevents the sensed waveform from the interference of environmental magnetic field [3]. On the contrary, magnetometer is subject to the interference from magnetic fields not generated by MagCode, *e.g.*, the geomagnetic field. Moreover, MICR reader scans checks at a constant speed, while MagCode is swiped by hand with a relatively unstable and arbitrary speed profile. As a result, decoding MagCode faces different challenges.

Magnetic stripe card [4] is a portable solution for conveying sensitive data, *e.g.*, bank account, staff ID, *etc.* Its data is stored in the magnetic materials (the stripe), and represented by the bars with different magnetic polarities. The card data is read by swiping through the card reader. At a high level, MagCode can be thought as a magnified stripe card. But since MagCode is printed on paper with ordinary printers, its manufacturing cost is much lower. Moreover, MagCode is readable through magnetometer that is prevalent in smart devices. Recently, magnetic materials are used in cloth fabric to store data in daily objects [15]. MagCode is a paper-based storage solution. It is low-cost and even disposable.

2.2 Interaction through Magnetism

In addition to data storage, magnetic materials are favored for their interaction implications in the HCI research. Permanent magnets and electric magnets have been explored for building various interactive interfaces, such as tangible and tactile interfaces [22, 29, 35]. The beauty of using magnets is the magnetic force, which is arguably the most affordable and convenient way for wirelessly producing haptic feedback [29, 37] and actuation [35]. The property of generating a wireless signal in the perceivable field is also used for activity recognition [11]. Moreover, the magnetic material (*i.e.*, ferromagnetic plastic material composed of iron fillings) is embedded into 3D printed objects, which can encode information invisibly and decode the information by swiping the magnetometers on smartphones over the 3D printed objects [19].

The combination of magnetic materials and paper has been explored by existing work [30, 37, 38]. FluxPaper [30] pastes magnet powder on a paper to allow the paper to auto-align to desired shapes and positions, and to move and vibrate on a whiteboard through an active electric magnet matrix. Magnetic Plotter [37] modifies a plotting machine to magnetize commercial magnetic sheets to generate simple stripe lines and even complex [38] magnetic field and on the sheet surface, which can be used for paper-based haptic feedback. MagCode differs from all of them. It is made by COTS (Commercial Off-The-Shelf) printer with ordinary papers, hence it is low-cost and ready-to-use. But as its magnetic field is not strong enough, it can not generate haptic feedback.

2.3 Barcode Variants

Barcodes have been widely used for physical labels and tags. There are many types of enhanced barcodes. For example, QR Code extends the capacity of 1D barcodes. A well-noticed issue of barcodes is the visual obtrusiveness. There are mainly two amortizing approaches. The first type is to use various colored, reshaped, and designed barcodes, such as Messenger Codes [5], Snapcodes [8], *etc.*, or to rely on drawing artifacts to hide information through, for example, topological features [16, 20]. Barcodes can also be totally hidden visually with invisible ink [21], or inside the object, which is only revealable by structured light [24].

MagCode belongs to the second type that conveys information in other signal domains. Acoustic barcodes hide information in physical notches of the object surface. It decodes through the scratch sound [18]. MagnetiCode [17] designs an active magnetic tag consisting of an electric magnet. It broadcasts information through varying the magnetic field. MagCode is similar to the concept of MagnetiCode, but its storage medium is passive and much more inexpensive.

2.4 Wearable Input Interface

Wearable devices are popular consumer electronics. Due to their tiny form factor and limited hardware resources, *e.g.*, small or none screen, conventional input interface designs are not suitable for them. The HCI community has explored novel ways to facilitate wearable interactions. WatchOut [40] leverages the smartwatch's inertial measurement unit (IMU) to extend the input vocabulary. They collect gyroscope and accelerometer data to recognize the user's gestures. Tapskin [39] further enrichs interaction by using acoustic signals. They use microphones to sense the movement to identify different tap locations. Then, they use the IMU to determine the arm displacement. Acoustic sensing alone is further shown to be a powerful approach that can be used for fine-grained gesture tracking [28]. There are approaches based on magnetometer like ours. Nenya [11] describes an input interface for wrist-worn devices. Nenya uses a magnet ring as the input tool, whose movement can be sensed by the magnetometer of the wrist-worn device. MagCode is different from the above designs in that the wearable device decodes for digital information

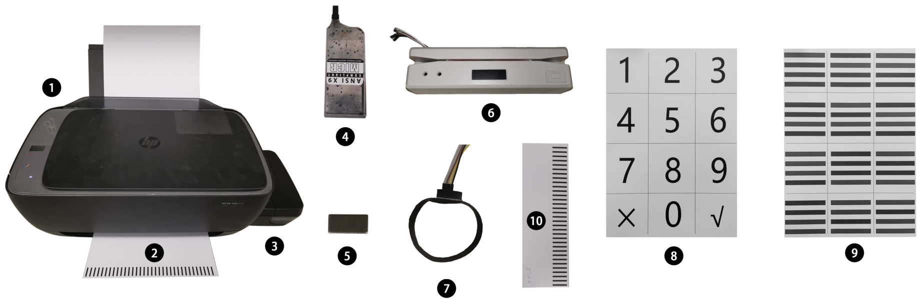


Fig. 2. **MagCode Labels and Related Items**. MagCode labels (❷❽❾❿) are printed by inkjet printers (❶) on ordinary office papers with the magnetic ink (❹) filled into the ink tank (❸). The printed MagCode label is first magnetized through swiping the permanent neodymium magnet (❺) over it. Then, the label can be read through either the dedicated MagCode reader (❻) or a smart device with magnetometer, *e.g.*, the wristband(❼). The front side (❽) of a MagCode label can be any designed drawing, *e.g.*, a keyboard. The back side hides the MagCode patterns (❾). The cash-size MagCode label (❿) is designed for offline digital payment.

rather than classifying signals for interaction purposes. Hence, the extracted information is more precise and much richer.

2.5 Barcode and Offline Digital Payment

One important application of barcodes is offline digital payment [1], where the payee scans the barcode of the payer to obtain the payment token to finish the transaction. As the payer does not require network connections, this payment paradigm is appealing when mobile networks are not available or stable. Researchers have noticed vulnerabilities if the security tokens in barcodes are leaked [12]. Several approaches are proposed to protect barcodes from being sniffed [32, 42], but they all target displayed barcode and leverage the properties of the display screen. On the contrary, MagCode can be used to enhance the security of offline payment in the printing form.

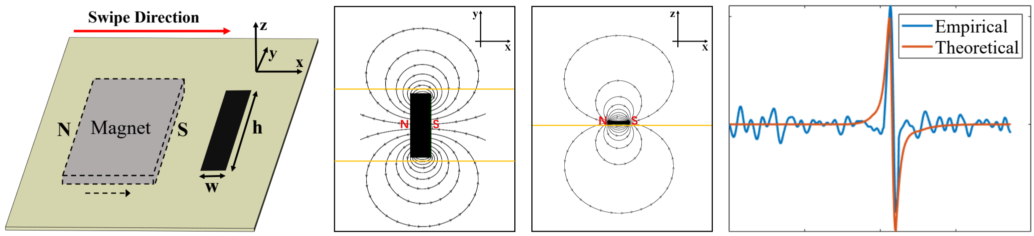
3 IMPLEMENTATION

MagCode is printed with magnetic ink. In this section, we first study the properties of the printed magnetic content. Then, based on the understandings, we propose simple but effective encoding and decoding schemes.

3.1 Properties of Magnetic Printing

3.1.1 Printing and Magnetization. Unlike existing work [30, 37] that uses dedicated instruments to fabricate artifacts having a strong magnetic field to leverage the magnetic force, we explore low-cost and ubiquitous methods to make use of the magnetism for data storage and interaction. To this end, we utilize Commercial Off-The-Shelf (COTS) printing devices and supplies to generate the desired magnetic field patterns. The printer is HP Ink Tank 310 inkjet (Figure 2 ❶). It has an external ink tank (Figure 2 ❸) for refilling supplies. The original black ink in the printer tank is replaced with the black MICR ink from VersaInk [9] (Figure 2 ❹). Laser printers can use compatible MICR cartridges. There is no special requirement for the printing paper. We feed heavy (160 g) white office paper for tenacity and durability.

The original magnetic ink and the printed content are not magnetized. The user can manually magnetize the printed label by swiping a magnet (Figure 2 ❺, permanent N35 neodymium magnet) over the printed content. The procedure is easy to conduct and can be finished instantly. Another



(a) (b) (c) (d)

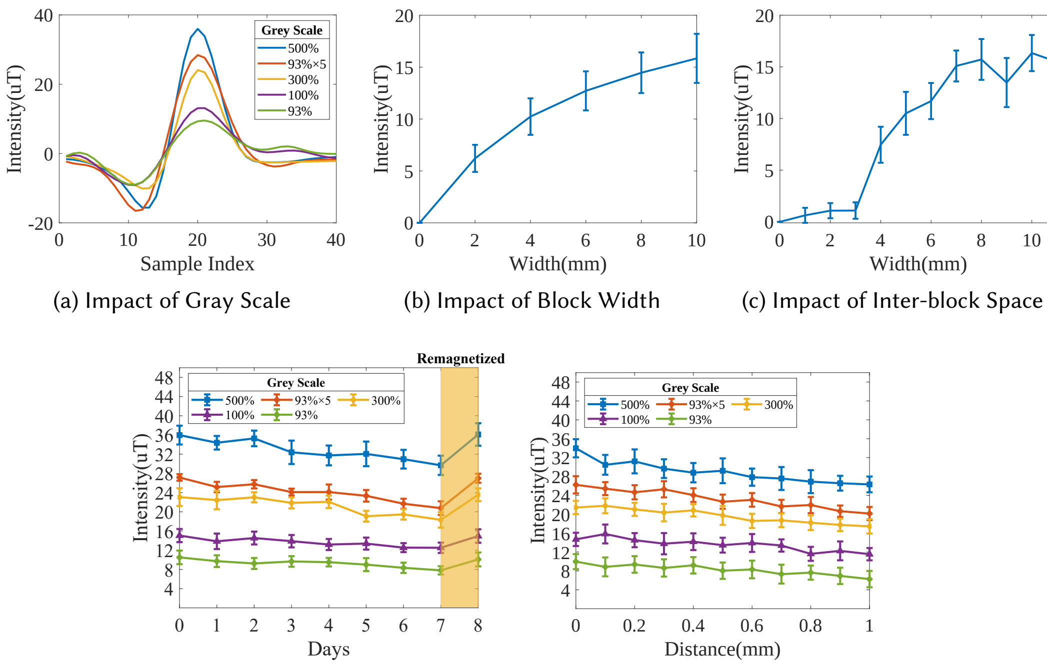
Fig. 3. **Magnetic Field of a Rectangular Block**. The magnetized rectangular block can be modeled as a thin rectangular magnet. (a) We measure the magnetic field intensity of the block by swiping the magnetometer across the block along the x+ direction. Since the magnet used for magnetization is swiped along the same direction, the block has a similar magnetization direction as the magnet. (b) and (c) are the top and horizontal views of the block's theoretical magnetic field when it is magnetized along the swiping direction, respectively. (d) shows the measured magnetic field intensity coincides with the theoretical model.

way is to fix the magnet to the printer's paper outlet. Then, the content will be automatically magnetized when the paper comes out from the printer.

3.1.2 Magnetism Properties of Printed Blocks. To understand the property of MICR printing, we start with measuring the magnetism of the rectangular black block with width w and height h. The block is also the basic building element of MagCode, which we will introduce in the next subsection §3.2. We study different impacting factors by swiping the magnetometer over the block along the arrow direction in Figure 3(a). The sensor is a HMC5883L 3-axis magnetic sensor connected to a Raspberry Pi. By default, the block size is h=2 cm and w=1 cm. The magnetometer reports the magnetic field in 3D vectors $<B_x, B_y, B_z>$. The overall intensity B is the norm of the vector, *i.e.*, $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$. The following results measure B after filtering the environmental magnetic interference (see the algorithm in §3.3.2).

High-level Overview. Theoretically, a magnetized rectangular block can be modeled as a thin rectangular magnet, whose magnetic field can be calculated with closed-form formulas [36] and viewed through ViziMag simulator [13, 14]. Figure 3 shows the recorded intensity changes when we swipe the sensor. The values have a coincident trend with the model. Here we ultimately chose a rectangle instead of a circle or triangle to implement MagCode because it is the most common and widely used shape. The theoretical model (magnetic field distribution of rectangular permanent magnets) also suggests that the perceived magnetic field intensity is determined by the density of magnetic particles (the gray scale of the block), the shape of the block, the neighbouring blocks, the magnetization decay, and the distance to the block. We will examine these factors one-by-one in the following.

Gray Scale. The gray scales, represented in percentages, determine the darkness of the block, 0% means white, 100% means black. Other values denote different gray colors in between. Values higher than 100% mean the block is printed more than once. For example, 300% means the block is printed 3 times with 100% gray scale. Figure 4(a) records the intensity values when swiping over blocks with different gray scales. The amplitude of the intensity changes increases with the gray scale. This is because a larger gray value means more ink is printed on the block and more magnetizable materials are contained in the block, which leads to higher field intensity.



(a) Impact of Gray Scale (b) Impact of Block Width (c) Impact of Inter-block Space

(d) Impact of Magnetization Decay (e) Impact of Sensor Distance

Fig. 4. **Properties of Magnetized Block**. (a) shows the magnetic intensity curves when we swipe the magnetometer over the blocks with different gray scales. (b) compares the peak intensity of blocks of different widths. (c) measures the amplitude of the curves with different inter-block space. (d) shows the trend of magnetic field decay over time. In day 8, the blocks are remagnetized. (e) measures the peak intensity of blocks with different distances from the magnetometer to the blocks.

Block Width. The dimension (*i.e.*, width and length) of the block also affects the magnetic field intensity. Since the length of the block is usually fixed for certain applications, we measure the impact by varying the block width from 0 mm to 10 mm. We record the positive peak value of the intensity curve of 100% gray scale in Figure 4(a) for comparison. As shown in Figure 4(b), the peak intensity increases with width. The results imply a trade-off. On the one hand, a wider block brings higher intensity, which is more resistant to noise. On the other hand, wider blocks consume more space, limiting the storage density.

Inter-block Interval. To make use of multiple blocks, it is necessary to understand the minimum separation required to distinguish adjacent blocks. Figure 3(d) shows the waveform of magnetic field intensity when swiping a magnetometer over single blocks. The waveform consists of positive and negative peaks. Considering multiple blocks, if the interval becomes smaller, the negative peak of the former block is influenced by the positive peak of the latter. The negative peak becomes larger and the positive peak becomes smaller. The intensity difference between the positive and negative peaks becomes smaller, which means that the impact of inter-block is increasing. We print multiple adjacent blocks of 100% gray scale. The width of the inter-block interval varies from 0 mm to 11 mm. We measure the amplitude (the intensity difference between the positive and negative peaks) of the block in the middle to see the impact. Figure 4(c) shows that when the interval is less than 4 mm, two peaks can not be separated. When the inter-block interval is larger than 7 mm, adjacent blocks no longer interfere with each other. This indicates that it is necessary to maintain sufficient space between adjacent blocks when they are independently used to represent information.

Magnetization Decay. Due to magnetization decay, the intensity of the block's magnetic field decreases over time. We record the peak intensity over one month and show the curves of first week in Figure 4(d). The magnetic fields of different gray scales have a similar decay trend. The decay speed is slow and hence the block does not need to be remagnetized frequently (remagnetization is highlighted by the shadow period between days 7 and 8 in Figure 4(d).). The magnetic field of 500% block takes about 35 days to decay to the intensity of the just-magnetized 100% block. This suggests that using dark gray scale and printing multiple times can prolong the durability of the block's magnetic field. Another interesting fact is that the intensity of the field is not linearly related to gray scale. This phenomenon can be observed from the absolute intensity values of different gray scales, especially the 93% one. The amount of magnetizable materials contained in the block (ink projection volume) is directly proportional to the magnetic intensity. However, the experimental results indicate that there is no linear relationship between the gray scales and magnetic intensity. This is because the printer does not linearly map the gray scales and the ink projection volume.

Sensor Distance. In practice, when sensing the magnetic field of the block, the sensor usually has a distance to the raw printed content due to the shield of the sensor or the cover of the block. We measure the peak intensity of the blocks by increasing the distance between the magnetometer and the block. To precisely control the distance, we cover the block with different numbers of A4 papers, and then swipe the magnetometer over it. As shown in Figure 4(e), the intensity decreases when the distance increases. We also observed that when the distance reaches 2 mm, the magnetic field can hardly be sensed by the magnetometer.

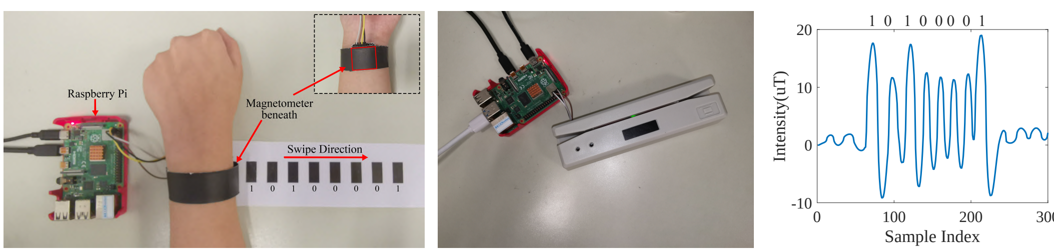
3.2 MagCode Label

Based on the above experiments and analysis, we propose the MagCode design to convey information in magnetic channel. A MagCode label consists of one or several aforementioned rectangular blocks arranged along a line or a curve. We note that barcode labels also use blocks to encode information, but MagCode cannot borrow their design due to the following reason.

A barcode reader is a 2D image sensor, which is able to precisely measure the geometric information of the barcode content. Hence, barcodes make use of the width and height of code blocks to convey information. However, MagCode is designed to be decodable by magnetic sensor, which is a 1D sensor. For a certain instant, the magnetometer can only measure the intensity of the magnetic field of a location, meaning that it has to rely on the user's swiping action to obtain the complete information of the magnetic field of the MagCode label. However, the user's swiping velocity is not stable. As a result, the block width and the inter-block space cannot be precisely recovered as well, making it hard to use the geometric information to convey information.

In order to solve this issue, instead of using the spatial information subject to the impact of swiping speed, we utilize the field intensity of the block to encode information. As measured in Figure 4(a), the field intensity is determined by the gray scale. As shown in Figure 5, the encoding scheme of MagCode is to use different gray scales to represent different bits, similar to the amplitude-shift-keying scheme in communication. We use dark black to represent bit "1", and light black to represent bit "0". To avoid interference from neighboring blocks (Figure 4(c)), we use white areas to separate the blocks. The block width, height, gray scales, and inter-block space are parameters affecting the information density as well as the form factor of the label. We will specify them later according to the application scenarios. Figure 5 shows an example of MagCode labels. It consists of evenly-spaced black and gray blocks (strip lines). The decoding process is described below.

Fig. 5. **Example of a MagCode Label**. MagCode encodes data into evenly-spaced black and gray rectangular blocks. It uses their difference in magnetic field intensity to convey information. The first two bits are used to compare the similarity of intensity for “1” and “0”. The CRC is used by the label reader to verify the correctness of decoding. For illustration, 70% gray scale is used for the gray lines in this figure. We note that in real MagCode labels, the gray scale is close to or larger than 100%. As a result, the blocks can hardly be differentiated from their visual appearance.



(a) (b) (c)

Fig. 6. **Two Types of MagCode Readers**. (a) we embed a magnetometer into a wristband to simulate general smart wearables. The user swipes the sensor over the label to sense the magnetic field. The recorded waveform is shown in (c). (b) is another type of reader modified from a commercial card reader by replacing the original sensor with the magnetometer. To decode the MagCode label, the user inserts and swipes the label in the reader like swiping a bank card.

3.3 MagCode Reader

3.3.1 Reader Hardware. MagCode labels can be decoded either through a smart device, like a wristband, or through a dedicated stripe card reader. They are internally the same and all based on magnetic sensors. As shown in Figure 6(a)(b), we prototype both types of readers based on the HMC5883L magnetometer used in the previous experiments in §3.1.2. The sensor is embedded into the wristband. For the card reader, we replace the original sensor of a commercial stripe card reader to the magnetometer. We use a Raspberry Pi to control and record the data from the sensor.

3.3.2 Reader Algorithm. Compared with the card reader case, the wristband case is more difficult to implement. This is because, instead of swiping the label, users tend to swipe the sensor over the label, leading to the movement of the magnetometer. Note that since the environmental magnetic field, *e.g.*, geomagnetic field (40 to 50 μT), is much stronger than the field of the MagCode blocks (several μT), changes in sensor position result in large fluctuations in the magnetometer readings, hiding useful information.

Our solution is based on the observation that the signals caused by the MagCode content are of higher frequency. So, before decoding, the magnetometer readings are pre-processed by a high-pass filter to eliminate the part contributed by the geomagnetic field. Then, we use the peak intensity to differentiate the bit “1” and bit “0”. Specifically, we calculate the magnetic field intensity through

Algorithm 1 Generate MagCode

Require: Length of all blocks *length*, Width of black or gray blocks *BitWidth*, Width of white blocks *InterWidth*, Gray scale of "0" *gray*, Bit String *bitstring*
Ensure: MagCode Image *magcode*

```
for bit in bitstring do
    if bit = 1 then
        magcode.draw(length, BitWidth, 100)
    else
        magcode.draw(length, BitWidth, gray)
    if bit is not the end then
        magcode.draw(length, InterWidth, 0)
```

Algorithm 2 Decode magnetic field intensity signals into bits

Require: Signals *inputSig*
Ensure: Decoded data *bit*

```
/* pre-processing */
uT = sqrt(pow(inputSig, 2))
Sig = eliminateGeo(uT)

/* select peaks out */
[peak, pos] = findpeaks(Sig)

/* map peaks into bits */
for p in peak do
    if p/peak("1") > threshold then
        bit.append(1)
    else
        bit.append(0)
```

the formula $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$. Then, the positive peaks are identified from the time series of B. For error checking and correction, if there is enough space for the content and the CRC code, users can design MagCode according to the example in Figure 5. The first two peak values corresponding to the first two bits "10" of the label are used as the reference to choose the appropriate threshold for differentiating the remaining bits. CRC is introduced at the end to check and correct errors. Otherwise, users can increase the intensity difference between bit "1" and bit "0" by repeating printing as we do in chapter 5, so that it is easier to distinguish the bit and reduce the error rate.

Take the label in Figure 6(a) for example. The label is printed with 93% and 100% gray scale for bit "0" and "1", respectively. The captured signal trace after removing the low-frequency parts is shown in Figure 6(c). 8 positive peaks can be identified. The intensity of the first and second bits is 17.6 μT and 11.7 μT, respectively. Their mean value is 14.7 μT. Bits of the remaining peaks are judged by comparing their values with 14.6 μT.

4 USING MAGCODE

MagCode is easy to use in daily life. The fabrication procedures include generating, printing and magnetizing.

The user first embeds the required information into a MagCode image through a generator script. Algorithm 1 is provided for developers to create their own MagCode labels according to application requirements. As shown, the generator script has 5 inputs, including the length of every single block, the width of each black or gray block, the width of each white block, the gray scale of the bit "0", and the bit string to be encoded. The output is the image of the MagCode to be printed.

Each bit is represented by a black or gray block. "1" in the bit string is fixedly represented by a black block with a gray value of 100%, and "0" is represented by a black block with the input gray value. Each colored block is separated by a white block to prevent magnetic fields from interfering with each other. Developers can design MagCode as needed. In order to easily identify changes in magnetic field intensity, our recommendation is that the size of the magnetic block can be as large as possible. The alternating black and white blocks format of the MagCode label allows for controlling the width of the blocks, which can help balance the bit string capacity with the magnetic field strength of each bit. Due to interference between magnetic blocks, we suggest that the width of the white area between blocks can not be less than 7mm. The script will continuously merge bit and interval blocks into the MagCode image according to settings.

For ordinary users, we aim to provide improved encapsulation programs. For example, in label-making mode, users simply need to input the desired size and all labels in sequence, and the corresponding MagCode labels along with recommended printing times will be generated. Similarly, in offline payment mode, entering the private key of the temporary wallet will fetch the corresponding MagCode label and recommended printing times for users.

The output image can then be printed on a paper label by inkjet or laser printers. The necessary requirement is that the printer has to use the MICR ink/cartridge, which is filled with metal particles for carrying magnetic signals. Limited by the number of magnetic particles in the ink, the magnetic code printed in a single pass is usually of low strength and is prone to identification errors. We usually need to increase the strength of the magnetic field through repeated printing to improve the decoding accuracy. In this work, we repeat printing 3 times. After printed out, the MagCode label can be decorated through covering it with arbitrary visual content since it does not rely on visual channels to decode.

When magnetizing the MagCode label, the user only needs a magnet to swipe over it. The swiping direction is directly along the direction of the blocks' width, which is shown in Figure 3(a). A magnetized MagCode label then generates a designated magnetic field representing the information that the user embeds.

To use the MagCode label, the user swipes a device with a magnetometer or digital compass over the code area. Then, the decoding algorithm demonstrated in Algorithm 2 will automatically extract the embedded information for further usage.

5 EXAMPLE APPLICATIONS

This section describes three applications to show the advantages of MagCode in interactive systems.

5.1 Decorative Object Labels

This application illustrates MagCode's advantages over conventional labeling techniques. MagCode labels are low-cost, versatile, and unobtrusive. They can be used to label objects while leaving their other side for decoration, or hiding invisibly, for example, under the mouse pad, beneath the tablecloth, or in the book. Figure 7 demonstrates a more specific application scenario: labeling smart home devices.

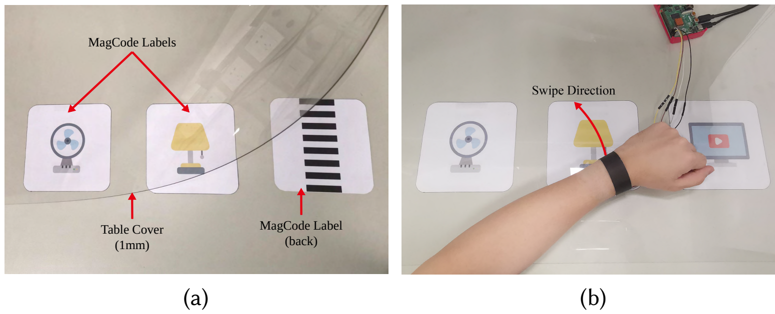


Fig. 7. **Application: Decorative Object Labels.** MagCode can be used to label smart home devices. (a) the back side of the label can be decorated consistently with the surroundings. The label can also work under the cover, *e.g.*, tablecloth. (b) when the wristband with the magnetometer is swiped over the label, it decodes the label content automatically and triggers corresponding application for device control actions.

Nowadays, smart home devices are becoming more prevalent. They provide an application to the smartphone for remote control. For example, turning on/off the light, the fan, and like that. However, with more and more devices like that, finding the correct control interface and the specific device to control is becoming more and more mentally overwhelming. One solution is to use shortcuts, but it will fall into a similar situation of searching among similar shortcuts.

MagCode labels can be used as a physical shortcut to the device. For example, we can put a label indicating the TV on the armrest of the sofa in the living room, *i.e.*, use the intuitive locations or physical icons as a hint to avoid searching overhead. Then, the user swipes the smart device, *e.g.*, smartphone or wearables, on the label, which automatically links to the TV application in the smart device. The application might have some pre-defined actions. For example, if it is swiped once, the TV will be turned on. If twice within a short period, the TV will be closed. For an experienced user to remember the label location and meanings, he/she does not even have to change the eye-gazing [10], which further facilitates smart home interactions.

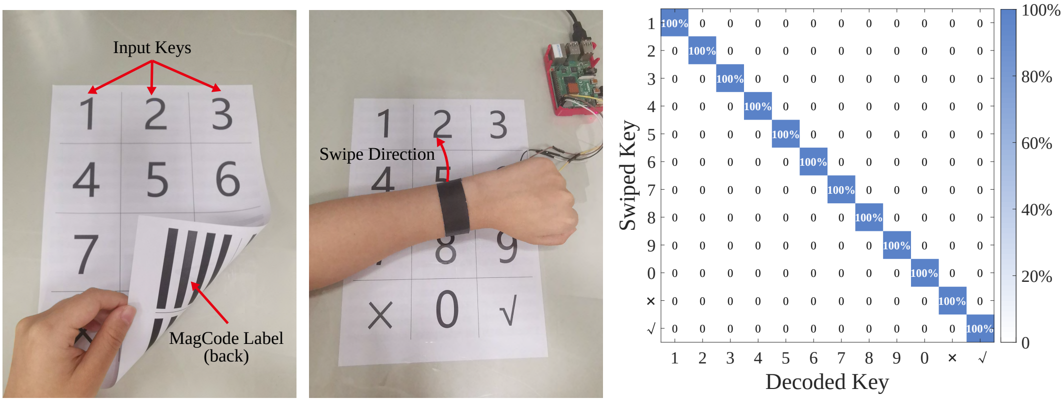
To enable robust decoding under an environment with strong magnetic fields, larger MagCode blocks are used. The block width is 10 mm and the height is 50 mm. The inter-block space is 9 mm. The grey scales are 93% $\times$ 3 and 300%.

5.2 Wearable Input Interface

Light-weight devices like wearables lack convenient input interfaces, which prevents them from being used in scenarios requiring complex user input, *e.g.*, verifying the password for payment, replying to an urgent email, *etc.* In this application, we show a portable keyboard based on MagCode labels, which allow for precise and efficient input for wearables.

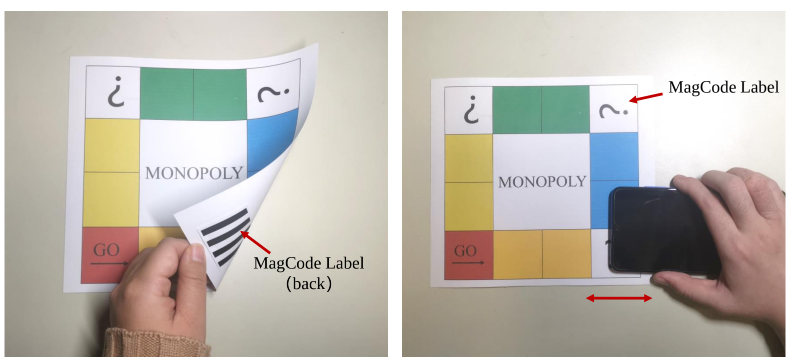
The keyboard is shown in Fig 8(a)(b). The user swipes the wearable device over it to input the key value to the device. The keyboard is made from an office paper. Its front is printed with ordinary ink, which includes numbers "0-9", "✕" and "✓". The back side of each key is a MagCode label. Each label has four blocks, *i.e.*, 4-bit information (the 2 header bits are ignored to save space). We map the 4-bit data to the keys. The block width is 7 mm and height is 50 mm. The inter-block space is 7 mm. We repeat the printing for three times and use 93% $\times$ 3 grey scale for bit "0" and 300% grey scale for bit "1".

By swiping the device from bottom to top over each key, the decoding algorithm can convert the magnetic signal into the key. Fig 8(c) is the confusion matrix of the decoding results. It shows



(a) (b) (c)

Fig. 8. **Application: Wearable Input Interface**.(a) a keyboard is printed on the front side of an office paper. The backside is printed with MagCode labels containing the corresponding key information. (b) the user swipes over the key content to input the corresponding key value. (c) the confusion matrix show the accuracy is 100%.



(a) (b)

Fig. 9. **Application: Tabletop Game Props.** MagCode can be combined with tabletop games. (a) use MagCode as a random event trigger in the typical tabletop game named "Monopoly". (b)users swipe MagCode along the direction of the question mark to achieve the random event.

a 100% correction rate. This implies that MagCode labels can be used as reliable and convenient input accessories for wearable devices.

5.3 Game Props

Recently, various kinds of sensor-based input scenarios are proposed to extend the interaction mode. PaperPulse [33] provides a novel and convenient approach for designers to produce standalone interactive paper artifacts by electronics. One of the applications is designing and fabricating a paper game named Hungry Monkey. The low-cost and unobtrusive properties of MagCode labels can also be combined with people's daily entertainments.

Traditional multi-player tabletop games, *e.g.*, Monopoly [31], have regular game rules, boards, and cards. It means that the interaction mode is fixed and lacking in flexibility. The extension of interaction is able to be achieved by MagCode. For example, hidden events allow the owner not to show event content to other players, giving more possibilities for games. MagCode is suitable to be utilized as a prop to indicate hidden events. The design of game board can refer to the pattern of puzzle using spliced squares. A part of the squares is selected to print MagCode labels which are non-visual for all players. The MagCode's block width is 5 mm and height is 40 mm. The inter-block space is 5 mm. We repeat the printing three times and use $93\% \times 3$ grey scale for bit "0" and 300% grey scale for bit "1". Every time the game starts, players randomly select the corresponding number of squares to assemble the game board, generating a random distribution of hidden events.

During the game, players roll the dice and move around the board according to the indicated number. As shown in Fig 9(a)(b), when moving to the "?" square, the player acquires the chance to trigger hidden events, *i.e.*, reward or penalty of Monopoly money. Not knowing the positions of hidden events at first, the player can choose only one square to swipe utilizing a smartphone. The square selected this time is not allowed to be chosen again. If the player correctly chooses a hidden event, the information of MagCode is sent to a specific application on smartphone to generate the event's content. Otherwise, the player just knows the selected square is not a hidden event trigger. Moreover, others are also not clear whether the player triggers a hidden event or not, requiring them to consider various kinds of conditions.

In addition, there is a promising direction to utilize magnetic decay as a means of limiting the validity period of game items. Since the magnetic decay of MagCode is not rapid, it allows for long-term activity props such as seasonal props. For instance, we can design cherry blossom tree props similar to those in "Animal Crossing". As the magnetism naturally decreases after the season, the props become invalid.

5.4 Offline Payment

MagCode enables a type of convenient passive storage with some properties desired by security applications. For example, MagCode does not use the visual channel, hence the content will not be leaked through optical ways like optical peeping. Further, as Figure 4(e) shows, the intensity of the magnetic field decays very fast with distance, which is even much faster than radios. Hence, unlike NFC labels [41], it is harder to sniff the MagCode labels remotely via magnetic sensors. Moreover, MagCode labels are low-cost and even disposable, which is suitable for storing temporary and one-time messages. Noticing the above properties, we believe that MagCode leads to new interaction forms in digital payment systems. In this subsection, we demonstrate using MagCode labels as a medium for physical offline payment.

Today's digital payment systems heavily rely on a smartphone, mobile networks, and online accounts, which are not convenient compared with the conventional cash system in some scenarios. For example, when the network is unstable and not available. Imagine another situation when the user wants to share gift money from his/her online digital account with a child having no digital account. He/she has no convenient means to do that right now. Similar situations appear with the elderly, the visually impaired, *etc.*

In Figure 10, as an example solution for the above problem, we show how MagCode can be integrated into the Bitcoin system [27] to enable offline payment. Conventionally, Bitcoin relies on network connections of the two peers to finish the transactions. To move it offline, we use a temp Bitcoin wallet as a disposable proxy for bridging the offline payer and payee. The credentials of the temp wallet are carried in a MagCode label, which is used offline for the payment.

Specifically, as shown in Figure 10(a). ① The Drawer (not necessarily the offline Payer) first creates a temp Bitcoin wallet, and then ② transfers a certain amount of Bitcoin money into the

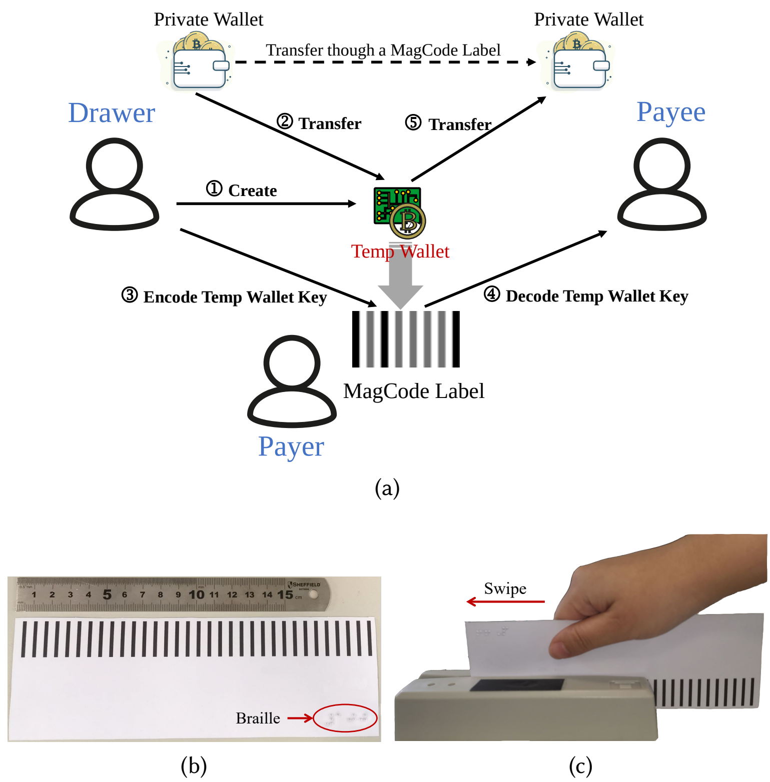


Fig. 10. **Application: Offline Payment**. (a) the flow graph shows typical offline payment procedures with MagCode labels. (b) the MagCode label used for the payment is printed in the size of normal cash. The label contains tactile Braille characters to hint the content, *e.g.*, the deposited amount in the label. (c) the modified card reader is used to extract the content in the MagCode label to get the payment credentials.

temp wallet. Next, ③ the `private key`, which is its unique address identifier and the authorized access proof, is stored and printed to a MagCode label. Note that anyone who successfully decodes this label can access the temp wallet and withdraw the stored money. The Drawer gives the label to the Payer. When the Payer needs to buy something offline, ④ he/she gives the label to the Payee, and ⑤ the Payee withdraws the money from the temp wallet.

In the above process, the Payer neither has a Bitcoin account nor network connections. There are plenty of technical details behind, which are out of the scope of this paper, but one related issue is the key length. The original Bitcoin private key is 256-bit, and 176 bits for a condensed version `minikey` [7]. The length still excesses the capacity of a MagCode label, as the label in Figure 10(b) carries 32-bit data. So, currently, we use multiple labels or large labels to contain one key. Another way is to improve the card reader in Figure 10(c), which will be discussed in §6.

6 LIMITATIONS AND DISCUSSION

This section discusses the limitations and possible improvements.

Low information density is one of the limitations. This is caused by two factors. First, the magnetic field decays very fast in space. The attenuation leads to weaker signal strength. In scenarios requiring high density, like §5.4, we can adopt more sensitive sensors to read MagCode labels. Second, the sampling rate of the magnetometer is low, which is only 100 Hz in normal platforms. Besides, when the swiping speed is fast, this sampling rate is not enough to fully recover the signals. Since it was found that some of the sampled data did not reach the maximum sampling rate given in the datasheet of the sensor, and sensors in commercial devices are usually difficult to modify. We believe one of the limitations of the low sampling rate is from the device's software driver, which could be modified to increase the rate instead of changing a sensor with a higher sampling rate.

The magnetic field of the MagCode label is generated by the magnetized metal particles in the ink. These particles are possible to be remagnetized by other nearby magnetic sources, which will distort the designated magnetic field. For example, a few daily items, such as bracelets, handbags, and wallets, are composed with permanent magnets. When doing important tasks (*i.e.*, offline payments) with MagCode labels, it is better to avoid those strong magnetic environments. Otherwise, the users have to remagnetize the MagCode label before reading it.

7 CONCLUSION

This paper describes MagCode label. It is printed with magnetic ink and relies on the magnetic field pattern to convey information. Its physical properties are measured and studied, based on that, simple and effective encoding and decoding schemes are proposed. MagCode is low-cost and easy to use. We demonstrate three applications to show their uniqueness and advantages in benefiting the interaction in different scenarios.

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