Data Storage and Interaction using Magnetized Fabric

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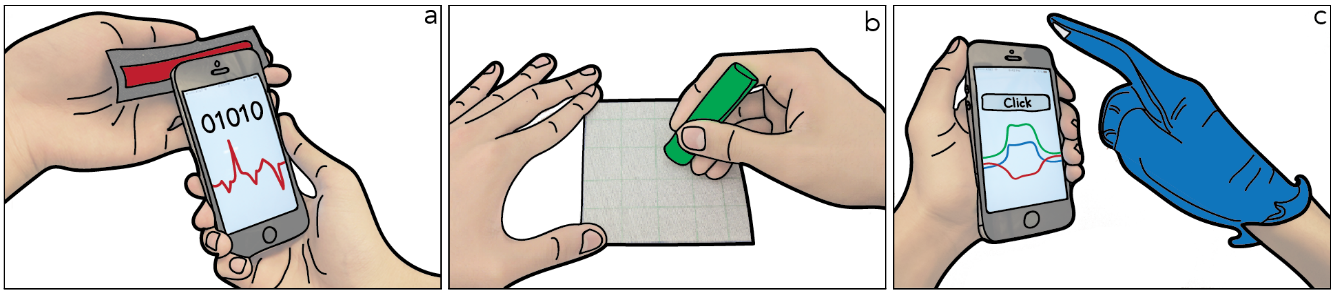

Figure 1: Example applications enabled by our design. (a) Store data onto textiles and read the bits by swiping a smartphone across its surface. (b) Draw a 2D magnetic image onto a cloth made of magnetized thread. (c) Magnetized thread enables users to gesture at a smartphone using a glove without electronics.

ABSTRACT
This paper enables data storage and interaction with smart fabric, without the need for onboard electronics or batteries. To do this, we present the first smart fabric design that harnesses the ferromagnetic properties of conductive thread. Specifically, we manipulate the polarity of magnetized fabric and encode different forms of data including 2D images and bit strings. These bits can be read by swiping a commodity smartphone across the fabric, using its inbuilt magnetometer. Our results show that magnetized fabric retains its data even after washing, drying and ironing. Using a glove made of magnetized fabric, we can also perform six gestures in front of a smartphone, with a classification accuracy of 90.1%. Finally, using magnetized thread, we create fashion accessories like necklaces, ties, wristbands and belts with data storage capabilities as well as enable authentication applications.

Author Keywords
Smart fabrics; E-textiles; Conductive thread

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION
The introduction of conductive threads and wearable electronics including the Lilypad Arduino microcontroller [16] and Google's Project Jacquard [35] has renewed the interest in everyday clothing as a computing and interaction platform. So far, the expressive capabilities of smart fabric have been primarily enabled by onboard electronics. This paper takes a contrarian approach and asks the following question: can we bring new computing and interaction capabilities to smart fabrics, *without the need for onboard electronics or batteries?*

A positive answer would reduce the fabrication complexity of smart fabrics and potentially increase their mainstream adoption. Imagine everyday clothing that has the memory to store images and codes without the burden of wires, batteries and communication electronics. Envision being able to perform gestures over a smartphone using a glove made completely and only of fabric. Such an approach would eliminate the need for waterproof casings that protect electronics against damage from rainwater and laundry cycles.

Our key insight is to leverage the magnetic properties of conductive thread and offload digital logic to an external device like a smartphone. We show that we can sense the presence or absence of magnetized thread using the magnetometers on smartphones. By manipulating the magnetic polarity of ferromagnetic thread, we demonstrate data storage on smart fabric as well as enable gesture recognition. Despite the growing interest in fabric computing, we are not aware of any work that has attempted to explore the data storage and interaction modalities enabled by magnetized conductive thread.

By taking a *completely passive approach* to smart fabric computing, we present the first smart fabric design that leverages the ferromagnetic properties of conductive thread to enable data storage and gesture recognition, without the need for any onboard electronics or batteries. Our approach can be fabricated with off-the-shelf embroidery machines and works with commodity smartphones and magnetometers. To demonstrate the potential of our approach, we describe three applications made possible by magnetized thread.

1. Data Storage. We store bit strings using magnetized smart fabrics and show that we can read it by swiping a smartphone along the textile. Conceptually this is similar to the way data is encoded on magnetic disk drives. A '0' and '1' bit can be encoded as a positive and negative magnetic polarity, which

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results in a positive or negative field strength at the magnetometer. We show that our data storage mechanism is reliable over time for more than a week. We conduct durability tests by washing, drying and ironing the magnetized fabric and show that we can recover all the bits after each test.

2. Imaging. We create a magnetic pen that uses the north and south poles of permanent magnets to imprint images on smart fabrics. We show that these images can be read by moving a magnetometer arbitrarily across the image or visualized in a single shot using an array of magnetometers. We demonstrate applications where a user can magnetically write characters onto a shirt that are invisible to the naked eye as well as create a secret code that can be scanned for authentication.

3. Gesture Recognition. We embroider magnetized thread onto the fingertips of a glove, which can be used to make gestures in the vicinity of a smartphone. At a high level, when a user performs a gesture, the magnetometer shows the varying magnetic field in the x, y and z axis. Each gesture produces a unique peak profile across the three signals, which we use for gesture recognition. We build a gesture classifier on our smartphone that works in real-time and can recognize six different gestures with an accuracy of 90.1%.

Finally, we prototype proof-of-concept applications that are enabled with magnetized fabric. We prototype a magnetic fabric reader that can scan a shirt and be used to unlock a door. We create fashion accessories including a wristband, necklace, tie and belt that can be used to store data. We also embroider magnetized strips onto shirts in different patterns and show that we can add data storage to clothing.

RELATED WORK

Flexible RFID. RFID tags store information electronically. However RFID readers can cost hundreds to thousands of dollars [12]. In contrast, magnetometers are as cheap as \$0.78 [5]. Further, a single roll of conductive thread costs \$17, and can create well over a hundred magnetized tags ($<$ \$0.17 per tag). In bulk, prices could be driven down even further. Our solution is affordable, accessible and works with smartphones, without investing into a costly and complicated RFID system. Finally, we note that magnetometers are low-power in nature — a LIS3MDL [5] can sample at $20\,\mathrm{Hz}$ with $72\,\mu\mathrm{W}$. In contrast, RFID readers [12] are 1000x more power hungry. With our approach, it is possible to create button-cell powered or battery-less magnetometer readers that harvest power from ambient RF, solar or human motion. This makes our design a compelling approach for interaction with IoT devices that may not have the real estate or power budget to run power hungry touchscreens [13].

Smart Fabrics. Recent textile-based computing projects [27, 32, 34–37] have focused on creating new fabrics with additional functionality. Project Jacquard [35] is a conductive yarn that can be weaved into touch-sensitive fabrics. Karma Chameleon [15] is a fabric that changes color in response to ambient light. Ambikraf [20, 33] uses thermo-chromic fabrics to create displays that change color. [18] fabricates solar cells using polymer fibers to harvest energy from sunlight and mechanical motion. Other textile-based projects [25, 31] use electronic components to build new interaction modalities on fabric. The Lilypad Arduino [16] is a toolkit that consists of a microcontroller, sensors and actuators that can be stitched together to build smart fabric projects. In contrast, our magnetized fabric approach does not require electronics and uses the ferromagnetic properties of conductive fabric.

Gesture Recognition. Recent work [9, 19, 21, 23, 26, 28, 29] adds permanent magnets to objects like fingers [17], pens [24], rings [38] and phone cases [22] to bring new input methods to mobile devices. In contrast, our approach uses conductive thread that induces a relatively weak magnetic field. We believe this is more attractive as our magnetized fabrics can be naturally integrated into textiles. In addition, magnetized thread can be placed next to objects like credit cards and hard disks, without erasing any data. This makes magnetized fabric more user-friendly for wider deployment.

DESIGN

We analyze different aspects of magnetized thread and use these findings to guide the design of our system.

Characterization of Magnetized Thread

We use BCP Conductive Sewing Thread [2], which had the highest magnetic field strength out of all the different brands of conductive threads that we tested. This material is ferromagnetic, which means that it initially has no magnetic field strength and needs to be magnetized with a permanent magnet. Initially, the magnetic domains of the conductive thread point in random directions. By magnetizing one section of conductive thread, we align all its magnetic domains in the same direction. The direction of the resultant magnetic field lines determine if the magnetic field strength is positive or negative. As smartphone magnetometers suffer from DC bias, positive/negative field strengths appear as increases or decreases from a stable baseline.

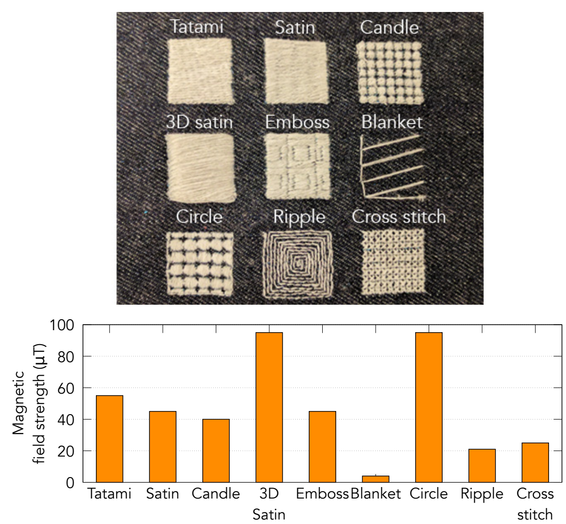

Figure 2: Embroidery styles. Different styles available through commercial embroidery software produce different magnetic field strengths.

For this analysis we magnetize the threads using a pair of N45 neodymium magnets with a diameter of 3.75 mm, a thickness of 1.5 mm and a separating air gap of 0.5 mm. This approach produces a magnetic field at the gap that is stronger than the field strengths of either magnet in isolation [3].

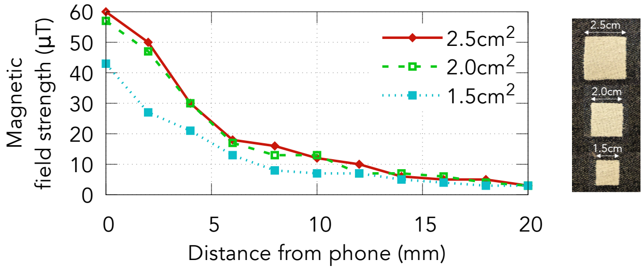

Figure 3: Magnetic field strength versus distance from phone. The field strength of magnetized fabric decreases with distance.

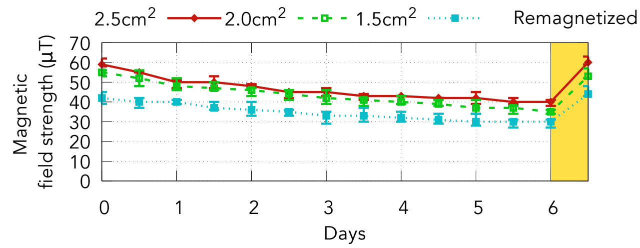

Figure 4: Magnetic decay over time. Three patches of magnetized thread lose between 28% to 36% of their original magnetic field strength over the course of a week. They regain their original field strengths after remagnetization at the end of the week.

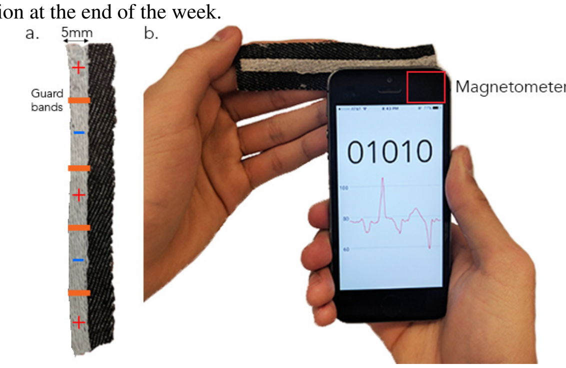

Figure 5: Magnetic code. (a) A magnetized strip polarized with positive and negative polarities. (b) User swipes smartphone across strip to read the bits.

In these experiments we embroider different square patches of magnetized thread onto a piece of fabric and measure their field strengths. To embroider the thread, we use the Brother SE400 [11] sewing and embroidery machine. We create our digital embroidery designs using Wilcom Hatch [4]. To measure the magnetic field strength of a magnetized patch we use the Nexus 5X smartphone [7] which has a built-in magnetometer with a sampling rate of 50 Hz.

Experiment 1: Embroidery Styles

In this experiment, we determine whether the embroidery style used to make a magnetized patch affects its magnetic field strength. We embroider nine patches of magnetized thread, each $2.5\,\mathrm{cm}^2$ in size. We magnetize them and measure their resultant magnetic field strengths using the magnetometer on our smartphone. Fig. 2 shows the magnetic field strengths for each of the nine styles tested. The two strongest designs are 3D satin and Circle. Despite the appealing material properties of these two designs, we opted to compromise for the Tatami design which has a flat and uniform surface texture that blends with regular fabrics and textiles.

Experiment 2: Field Strength Decay Over Distance

Two additional parameters are 1) the size of our magnetized patches and 2) the distance at which the patches can be detected. Intuitively, the magnetic field strength of a patch increases with its size. However, using large patches of magnetized thread could reduce the encoded bit density.

We embroider three square patches with dimensions $2.5\,\mathrm{cm}^2$, $2\,\mathrm{cm}^2$ and $1.5\,\mathrm{cm}^2$ and measure them at increasing distances as seen in Fig. 3. We use plastic sheets to maintain a constant distance between the magnetized patches and the smartphone. As distance increases, the measured magnetic field strength decreases quickly. Additionally, the field strength of a patch increases with its size. The field strengths of each patch converges to $3\,\mu\mathrm{T}$, which is close to the noise floor of $1\,\mu\mathrm{T}$ on our smartphone. Due to the fast drop-off in field strength over distance, the presence of magnetized thread will be most pronounced when it is within 5 mm of a magnetometer.

Experiment 3: Field Strength Decay Over Time

We evaluate how the passage of time affects the magnetic field strength of magnetized thread. To do this we embroider three magnetized patches of sizes $2.5\,\mathrm{cm}^2$, $2.0\,\mathrm{cm}^2$ and $1.5\,\mathrm{cm}^2$ and measure their field strengths twice a day over the course of a week. We then remagnetize each patch at the end of the week. Fig. 4 plots the decay in magnetic field strength of the three fabric patches as a function of time. The large, medium and small patches lose 32%, 36%, 28% of their magnetic field strength respectively. As the small patch maintains a relatively stable magnetic field strength over time, it is likely that all the patches will continue to retain some measurable magnetic field strength even after a few weeks.

Data Storage

Our first application of magnetized thread is a data storage scheme on textiles that can be read on a smartphone. To achieve this, we embroider a strip of magnetized thread that acts as a reprogrammable data storage medium. As shown in Fig. 5, we divide the strip into cells where each cell is encoded with a single bit. To encode the data, we polarize each cell with a north or south magnetic field using a permanent magnet, which corresponds to a 1 or 0 bit respectively. In order to see the peaks clearly on a smartphone, we intersperse each cell with unmagnetized portions of conductive thread, which act as guard bands preventing intersymbol interference. The data can then be read by simply swiping the magnetized strip across a smartphone. In our design, we use magnetized patches with a width as small as 5 mm. Each cell and guard band are 2 cm and 1 cm respectively.

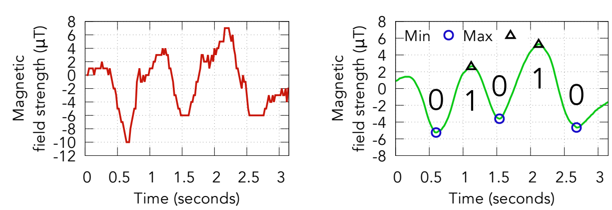

Figure 6: Encoding data into fabric. (Left) Raw x axis signal from smartphone's magnetometer. (Right) Smoothed signal and identified peaks.

Fig. 5 shows a user swiping a phone across the magnetized patch to read a bit string corresponding to 01010. When scan-

Algorithm 1 Reader

```
function READ(signal)
    smoothed ← average(signal)
    peaks ← findpeaks(smoothed)
    for peak p in peaks do
        if dist(p, p + 1) < minDist or
            peakWidth(p) < minPeakWidth or
            peakHeight(p) < minPeakHeight or
            !IsProminent(p, minProminence) then
            discard p
    return [1 if isMax(p) else for p in peaks] // Map peaks to bits

function ISPROMINENT(peak, minProminence)
    [p1, p2] ← highest peak to left/right of peak
    [min1, min2] ← global min in [p1, peak]/[peak, p2]
    prominence ← first peak above max(min1, min2)
    return prominence ≥ minProminence
```

ning the strip across the x-axis of the smartphone's magnetometer, we see maxima and minima corresponding to the 1 and 0 bit encoded on the magnetized fabric strip.

We smooth the raw 50 Hz signal with a window size of 20 samples. Then we identify all the peaks in the signal by looking for samples with neighbors that both have a lower or higher value. Due to environmental noise and sensor bias, we need to discard irrelevant peaks that do not correspond to data. We filter through the list of raw peaks and map maxima to a 1 bit and minima to a 0 bit. Our filter checks that a peak is at least 20 samples away from the previous peak, has a minimum width of 10 samples, a minimum height difference of 0.4 from neighbors 10 samples away and a minimum prominence of 0.1. The prominence of a peak quantifies how well it stands out from other peaks in the signal.

IMAGING

Our second capability is to use magnetized fabrics as a canvas that a user can use to 'draw' invisible images.

Figure 7: Imaging. (a) 3D printed magnetic pens. (b) Drawing a magnetic image onto a piece of magnetized fabric (c) Decoding the image by scanning a single magnetometer randomly around the image.

At a high level, we polarize sections of magnetized fabric with different polarities to create magnetic images. A north polarity corresponds to filled space and a south polarity corresponds to empty space. We polarize the fabric using permanent magnets integrated into a pen form factor. Fig. 7(a) shows two 3D printed magnetic pens. A small magnet is glued to the bottom of the pen. The red pen writes data with a positive magnetic field. The blue pen erases data with a negative magnetic field. Fig. 7(b) shows the user drawing a magnetic image onto a 9 cm^2 piece of magnetized fabric. The user 'colors' in each cell with either a north or south field.

We use a standalone magnetometer chip instead of a smartphone's magnetometer to read the images. We do this because a smartphone's magnetometer is enclosed in a larger case, and it is difficult to place it precisely over different sections of the magnetized cloth. We use the Memsic MMC3416xPJ [6] magnetometer which we sampled at 50 Hz at a resolution of 16-bits. We also take the Euclidean distance of the x, y, z values from the magnetometer to get a single field strength value. We employ two approaches to decoding the magnetic images using the magnetometers.

1) We move the magnetometer randomly over the fabric using the setup in Fig. 7(c). The SparkFun ZX distance infrared sensor [14] localizes the magnetometer. It can sense objects up to 25 cm away and 15 cm across. We combine readings from the infrared sensor and magnetometer that fall within the same time window and average the field strength values.

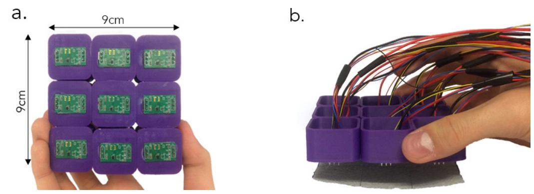

Figure 8: Magnetometer array. (a) A 3x3 array of magnetometers. (b) Scanning magnetized fabric in one shot.

2) To read a magnetized patch divided into a N by N array in one shot, we use a N by N array of magnetometers as shown in Fig. 8(a) where N is three. Fig. 8(b) shows a user hovering the array over the magnetized fabric to read its values.

GESTURE RECOGNITION

Our gesture recognition system uses a glove with fingertips that have an embroidered patch of magnetized thread as seen in Fig. 10(a). The patch is 2 cm^2 in size and fits onto the glove's fingertip without impeding a user's ability to grasp and manipulate objects. To detect gestures we use the tri-axis magnetometer on a smartphone which outputs field strengths along an x, y and z axis. Fig. 10(b) shows a user wearing the glove and interacting with the smartphone by making gestures across the phone's magnetometer.

Fig. 9 shows six gestures, that can be classified in real time on a smartphone. We first average the x, y, z values with a window of 20 samples to produce a smoothed signal. We then identify and filter the peaks of the resulting signal. Finally, we map the relative positions and amplitudes of all current peaks to different gestures. A challenge with using a magnetometer is dealing with the large-scale variances in magnetic field readings as the smartphone's orientation towards the Earth's magnetic poles changes when the phone moves. The variances in magnetic field readings that are produced when moving a phone dominate the small fluctuations caused by a user's gestures. As a result, it is difficult to extract the user's gestures as the smartphone is in motion. To cope with this, we use the smartphone's accelerometer and gyroscope to detect the smartphone's movements, and pause readings from the magnetometer when we determine that the smartphone is moving or rotating too much within a given time window.

Finally, Fig. 3 shows that we lose approximately 60% of a patch's magnetic field strength beyond distances of 5 mm from the smartphone. Thus, we perform our gestures with the glove placed tangent to the smartphone. We believe it is possible to manufacture conductive threads with higher field

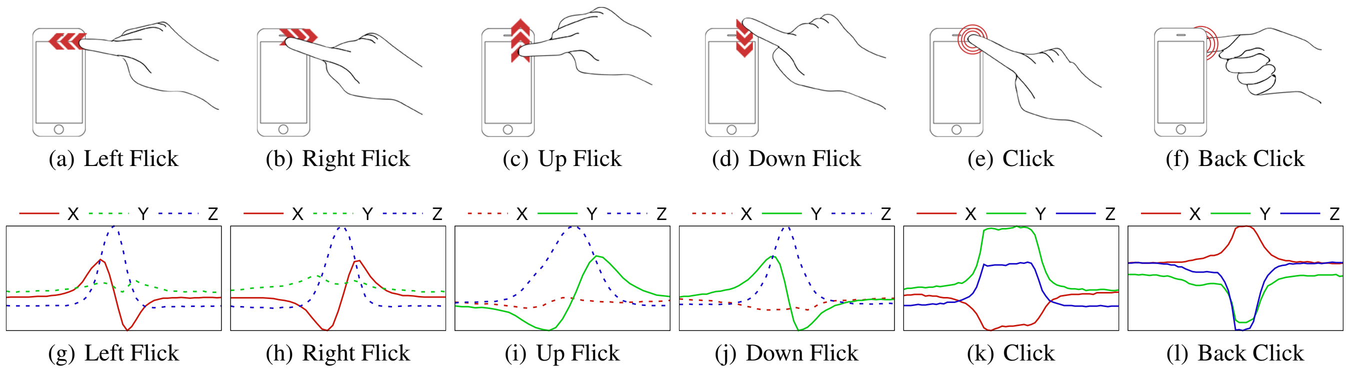

Figure 9: Time-domain signal profiles of gestures. Magnetic field strength changes on the x, y, z axes map to unique gestures.

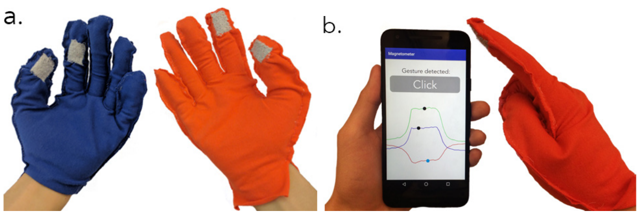

Figure 10: Performing Gestures. (a) Glove with magnetized fingertips. (b) User performs gestures for a smartphone with the magnetized glove.

strengths that can be sensed at a further distance from a smartphone. However, that is not within the scope of this project.

EVALUATION

We evaluate each of our data storage, imaging and gesture recognition techniques.

Data Storage

Durability

We stress test the durability of our magnetized fabric after ironing, washing and drying. The magnetized fabric that we test consists of ten $2\,\text{cm}^2$ patches that are lined up along the same axis. We alternate the polarization of each patch so that south fields separate north fields. All tests were conducted within a single session and we magnetized the patches once at the beginning of the session.

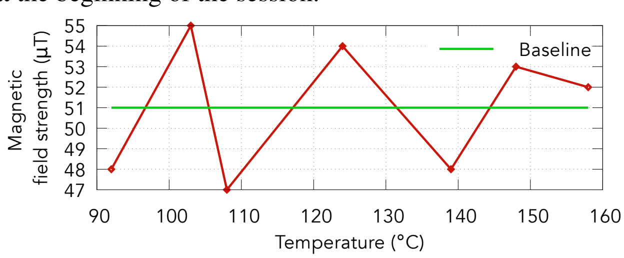

Figure 11: Ironing and temperature test. High temperatures do not affect the magnetic field strength across peaks. The small deviations in field strength are an expected result of using fabric as a data storage medium.

First, we iron the magnetized patches at different temperatures and measure the changes in magnetic field strength as seen in Fig. 11. We use the iron to apply steam to the magnetized patches, and move the iron over the patches several times. We used a meat thermometer to gauge the iron's temperature. For a given temperature setting, the iron's temperature fluctuates within a small window. So, we record the maximum observed temperature. Our results show that the resultant changes in magnetic field strength stay within $4\,\mu\text{T}$ of the $51\,\mu\text{T}$ baseline. This shows that heat has little to no effect on the memory of magnetized thread.

Condition	Average decrease in field strength
Hand Wash	$6\,\mu\text{T}$
Machine Wash	$3\,\mu\text{T}$
Drying	$5\,\mu\text{T}$

Table 1: Durability testing with washing/drying.

Next, we hand wash the magnetized patches for several minutes. We then place the patches in a washing machine along with other clothes and laundry powder. The patches were then placed in a dryer. The washing machine and dryer each ran for approximately one hour. Table. 1 shows the average reduction in field strength of each magnetized patch with respect to a baseline value that was measured before the durability tests. The changes in magnetic field strength are small and are equivalent to the natural fluctuations in readings. We were able to recover all bits after each durability test.

Reprogrammability

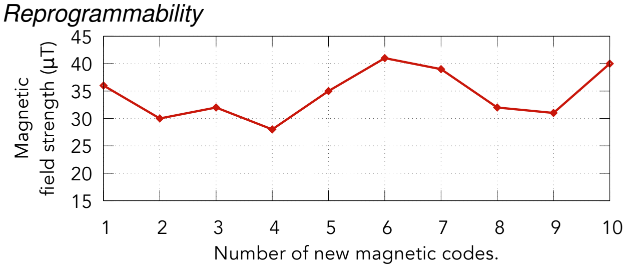

Figure 12: Reprogrammability of magnetized fabric. Adding new data to the same fabric strip has no substantial effect on its ability to store data.

To show that magnetized strips can be reprogrammed, we programmed ten different sets of five bits onto the same magnetic strip. Fig. 12 shows the average measured magnetic field strength of each bit after each set of bits is programmed. The key thing to note is that there is no noticeable degradation. The changes in the signal are natural measurement variances that occur as a result of using fabric as a data storage medium.

Imaging

We evaluate the resolution at which we can encode magnetic images. We divide a 9 by 9 cm patch of magnetized fabric into grids of different sizes and draw a pattern onto it with a permanent magnet. We test grid sizes of 3x3, 4x4 and 5x5. We do not test higher resolution grids because our magnetometer, which has dimensions 2.1 by 1.2 cm, would physically overlap two cells, and thus suffer from inter-symbol

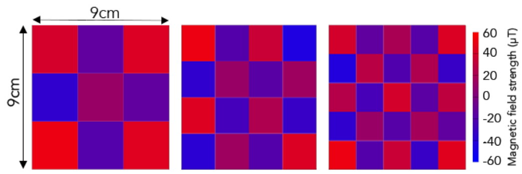

Figure 13: Resolutions of magnetic images. We can encode data reliably on 3x3, 4x4 and 5x5 patches.

interference from multiple independent magnetic fields. We encode a dense checkerboard pattern onto each of the magnetized patches.

As seen in Fig. 13 we are able to embed a checkerboard pattern on each of these patches. The magnitude of magnetic field strength can vary within a single cell. This is because it is difficult to impose a perfectly uniform magnetic field into a confined space of conductive thread. However, we observe a clear positive or negative peak when the magnetometer is placed at the center of a cell, and can read the stored image.

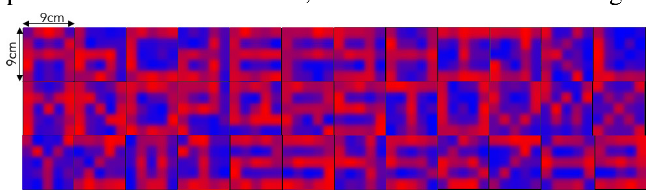

Figure 14: Symbols that can be encoded on magnetized fabric. It is possible to encode all 26 letters of the alphabet and all 10 numeric digits.

To show the expressiveness of magnetized fabric as a visualization medium, we draw all 26 letters and all 10 numerals on different 5x5 magnetized patches. Fig. 14 shows the interpolated heat maps of the magnetic field distribution for each encoded symbol. Using this set of symbols it is easy for users to put together images that correspond to their name, their current mood or the weather. We can comfortably fit four magnetized letters across the chest of a size S T-shirt. We believe that with smaller magnetometers, it would be possible to encode bitmap images onto the fabric and view the images in real time by hovering a magnetometer array over the patch.

Gesture Recognition

Actual Gesture Performed \ Gesture Classified	Up	Down	Left	Right	Click	Back Click	Not seen
Up	0.91	0.01	0	0.01	0.04	0.03	0
Down	0	0.9	0.02	0.03	0.03	0.01	0
Left	0	0.03	0.87	0.06	0.02	0.01	0
Right	0.04	0	0	0.94	0.02	0.01	0
Click	0.01	0.01	0	0.01	0.92	0.02	0.02
Back Click	0	0.06	0	0.02	0.04	0.86	0.03

Figure 15: Confusion matrix for gesture recognition. Average classification accuracy across all gestures and users is 90.1%.

We recruited seven participants, all right-handed users whose age was between 19 and 26. The participants were not offered any monetary benefits for taking part in the study. The study was split into two rounds and in total lasted for approximately 30 minutes. We began the session training each participant how to perform each gesture. The participants were then asked to wear a glove embroidered with magnetized thread and to perform a gesture ten times in a row for each gesture. They were then instructed to take off the gloves for a few minutes while we asked them several questions about their experience. We asked them to wear the glove again and repeat the same procedure for another round.

Our real-time classifier recorded an accuracy of 90.1% (SD=5.03%) across all six gestures and seven participants. Fig. 15 shows the confusion matrix of our classifier across all gestures. Fig. 16 plots the classification accuracy for each of the two rounds that each participant took part in. The accuracy for all but one user increased in the second round, which suggests that making accurate gestures with magnetized thread is a task that can be learned over time.

Finally, participants reported that the magnetized patches on the gloves had a mean comfort level of 4.07 (SD=0.94) (1=restrictive, 5=no difference). The act of performing gestures with the gloves in a public venue was rated with a social acceptability score of 4.28 (SD=0.70) (1=socially unacceptable, 5=socially acceptable). These high confidence ratings indicate that our approach to gesture recognition is unobtrusive and appropriate in public settings.

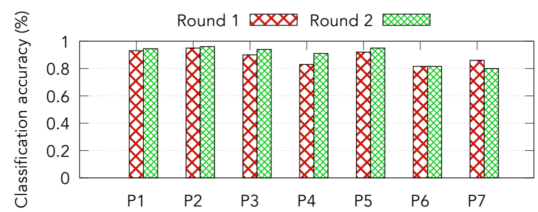

Figure 16: Classification accuracy per user per round. For all but one participant, all other participants perform more accurate gestures after a break in between testing rounds.

Through-pocket sensing

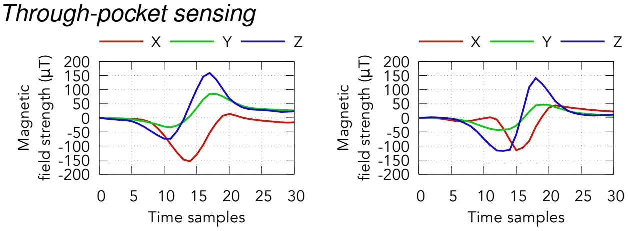

Figure 17: Gesture recognition through the pocket. Time-domain signal when glove is in contact with phone (left) and phone is in pocket (right)

Fig. 17 shows the time-domain signal for a left swipe gesture when the phone is in contact with the glove and when it is in the pocket. As can be seen the small layer of fabric only marginally dampens the magnitude of the magnetic field. The main features of the signal are however preserved; thus allowing us to perform gesture classification through the pocket.

False Positives in Different Environments

To characterize the practicality of our gesture recognition system in the wild, we measured the number of false positives detected by our classifier in a variety of scenarios. One of the challenges of using a magnetometer for gesture recognition is that magnetic field strength readings change based on the smartphone's orientation towards the Earth's magnetic poles.

Fig. 18 plots the number of false positives detected by our classifier when a user engages in three different activities each

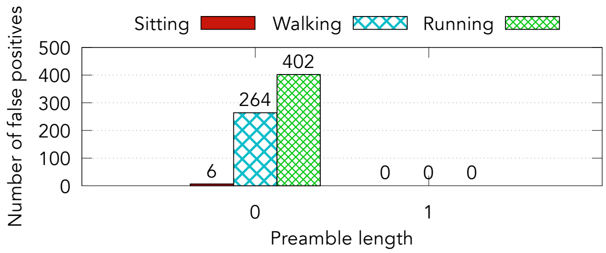

Figure 18: False positives in different settings. A preamble length with just one gesture reduces false positives to zero in all three conditions.

measured over a 30 minute period. While sitting, the user accumulates a relatively small number of false positives. However, walking and running increases the number of false positives significantly. This occurs even when the magnetometer readings are paused during large movements.

We instead include a preamble to help reduce false positives. We discovered that false positive gestures were limited to up, down, left and right gestures. We introduce a single back click gesture as a preamble, which reduced the number of false positives to zero in all three scenarios.

Power consumption

The battery on a Nexus 5X lasts for 22 hours. Leaving the magnetometer on without the classifier running reduces the smartphone's overall battery life by 4 hours or 18%. Our classifier does not cause any additional decreases to the battery life. This depletion in battery life is because magnetometers on Android phones are designated as non-low-power sensors [1]. However, it is possible to implement magnetic gesture recognition rules using a system on chip integrated circuit which can be optimized to run at a low power.

PROOF-OF-CONCEPT APPLICATIONS

Figure 19: Using a magnetic patch for authentication. Magnetized fabric can be an alternative to RFID cards and used to unlock doors.

Authentication. Fig. 19 shows how magnetized fabric could be used as an alternative to RFID keycards [8, 10, 30]. We envision that users would wear a shirt with a magnetized fabric patch sewn near the cuff. The magnetized fabric patch would be encoded with a special identifying image. The user would then scan his shirt across an array of magnetometers, which would process the magnetic field strength signals on a microprocessor. If the signals match a predefined pattern, the door is unlocked. With a 5x5 grid, it is possible to encode 2^{25} unique patterns which is sufficient for many applications.

Fashion Accessories. Using magnetized thread, we embroider and sew fashion accessories like the necklace (60 cm), necktie (45 cm), wristband (20 cm) and belt (90 cm) in Fig. 20. Using our data storage scheme we can encode 20, 15, 6 and 30 bits respectively onto these accessories. Magnetic data can be encoded along these small and defined surfaces and decoded using a smartphone. Using magnetized yarns, it is possible to crochet or knit larger fabrics and apparel like shirts and hats

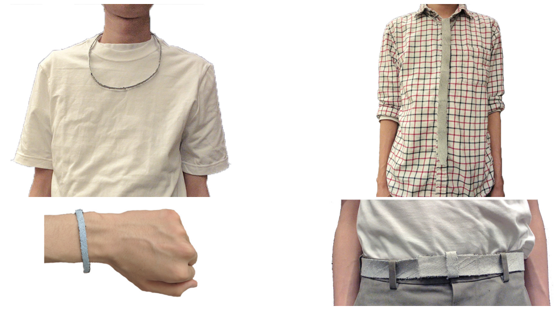

Figure 20: Fashion accessories made with magnetized thread. We create a necklace, necktie, wristband and belt that stores data.

that are entirely ferromagnetic. Encoding and decoding magnetic information on such large irregular surfaces would be worthwhile future work.

DISCUSSION AND CONCLUSION

We provide the first characterization of the magnetic properties of conductive thread. We showcase a set of novel data storage and interaction capabilities with magnetized thread that enhances the use of smart fabric as a computing medium. In this section, we outline discuss various aspects of our technology and outline avenues for future research.

Demagnetization. Our data storage system is susceptible to demagnetization in a similar way that magnetic hard disks and hotel key cards can be erased when placed in a strong magnetic field. As commercially available conductive threads have a weak magnetic field strength, they are best suited for storing temporary messages. With custom magnetic fabric, we could create stronger magnetic fields that are more resilient to external magnetic fields.

Tracking complex gestures. Our work focuses on classifying coarse-grained actions made with one finger. Our classifier relies on hard-coded rules and does not require prior training. However, there is nothing that fundamentally limits us from recognizing more fine-grained inputs like words being written in mid-air or complex gestures made with four or five fingers. Such a system would require textiles designed to radiate a stronger magnetic fields that could be detected further from the phone. Such a task would need multiple magnetometers to separate movements created by each finger.

Mobility. The readings from a magnetometer change depending on its orientation to the Earth's magnetic poles. As a result our magnetometer must be stationary to avoid drastic changes in the sensor's output. In order to get stable magnetometer readings in a mobile environment, we would have to compensate the raw sensor readings with data from an accelerometer or gyroscope. This is feasible in the case of smartphones where all three sensors are packaged onto the device.

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