

MagnID: Tracking Multiple Magnetic Tokens

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ABSTRACT

Tangible systems present compelling interaction opportunities but are typically enabled by complex, bulky, awkward or expensive sensing infrastructures. This hinders their adoption in many application areas. In order to address this issue, this paper explores the use of simple active magnetic tokens that create carefully controlled patterns of varying magnetic flux as the building blocks of tangible systems. We describe the construction of these tokens and a software system capable of detecting their presence and inferring their location based on data sampled from a single triaxial magnetometer - a standard component of most current mobile devices. The system can recognize token positions from a set of six pre-calibrated locations with an accuracy of 99%. We describe the hardware and software components of this system and five demonstration applications that illustrate its functionality.

Author Keywords

Magnet; Near-Device Interaction; Tangible Interaction.

ACM Classification Keywords

H.5.2 [Information interfaces and presentation]: User Interfaces. – Input devices and strategies.

INTRODUCTION

Tangible interaction is a compelling paradigm in which users manipulate real objects to control digital contents [23, 24]. It promises to bring the benefits of physical affordance, fine-grained manipulation and natural understandings to interaction with virtual contents. However, while potentially powerful, most current tangible systems are also inaccessible to most users as they rely on large and expensive sensing infrastructures, such as tabletop computers [11]. We argue this dependency has hindered the adoption, development and deployment of tangible interfaces in real world applications and to real world users.

Numerous authors have made similar observations and there has been a recent trend to develop tangible systems based on the sensing capabilities of modern mobile devices - low cost and prevalent hardware platforms. One approach

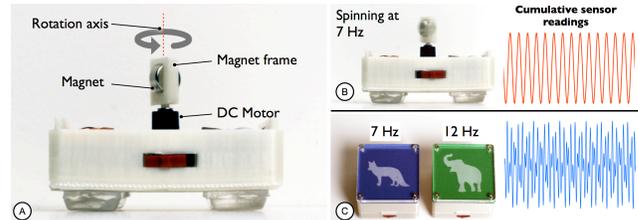


Figure 1. MagnID tokens work by spinning a magnet with a motor (A). A magnetometer senses changes of polarity as a continuous wave with a specific frequency (B, C).

has been to use visual tracking techniques [1], but these require bulky additional physical setups to ensure clear visual fields of view onto tracked objects. Another approach has been to create systems of tokens that can be placed on the touch screen of devices. Through careful design involving conductive materials placed on capacitive screens, these tokens create unique and recognizable patterns of on-screen touches that can be mapped to object tracking [5] or control activity [25]. While this is powerful, such systems suffer from inherent limitations: available screen size is small and the number of objects and touches that devices can recognize is relatively low (typically between two and four independently tracked objects based on a maximum of five to 11 touch points), restricting the expressive potential of such approaches.

Another approach has been to embed magnets in tokens or objects [e.g., 3, 8]. These can be sensed by the on-board magnetometers present in modern mobile devices and confer numerous advantages - magnets require no power, are inexpensive and can be detected both on and around a device. Reflecting these advantages researchers have built a range of systems for tasks such as device customization [10], cursor control [7], or adding physical buttons, sliders and dials to the area around a device [8]. However, a fundamental limitation of such systems is that magnetometers return a single aggregate vector summing the magnetic fields surrounding them. This makes it challenging to create systems based on more than one independently tracked object or token. While some authors have trained recognizers to achieve this objective when the available movements are highly restricted in scope [3, 8], there is no currently available system based on commodity sensors such as magnetometers that can recognize the independent location of a set of tokens based the magnetic fields they generate.

This paper aims to address this issue by designing and developing MagnID, a novel magnetic object tracking

system. The main contribution of this paper is the design of the system. It innovates over prior work by supporting tracking multiple magnetic tokens simultaneously, in locations both on and around a device and via data recorded from a single magnetometer. Secondary contributions are a description and characterization of the performance of one possible implementation of the MagnID concept, and the presentation of five demonstration applications that highlight the design space enabled by MagnID.

RELATED WORK

Sensing magnets offer many advantages for mobile interaction. Magnets themselves are small, inexpensive, unpowered components [7]. Furthermore, high precision triaxial magnetometers are a standard feature of modern mobile devices and tablets. Finally, magnetic fields are largely immune to issues of field-of-view - magnetic interaction systems can function seamlessly in the spherical volume surrounding a single sensor. However there are also challenges unique to magnetic tracking. Typical magnetic sensors (e.g. triaxial magnetometers) return a cumulative reading derived from all the magnetic fields affecting the sensor (including those attributable to environmental noise) effectively making accurate disambiguation of multiple independent magnetic sources an under-constrained problem - there are many possible solutions for any given state. Dipole magnetic field strength (such that generated by many common permanent magnets) also varies with the inverse-cube of distance, meaning that small spatial displacements of magnets near the sensor results in greater changes to detected data than relatively large displacements of more distant magnets [22]. Combining the properties and features of this sensing channel, researchers have developed a wide range of interaction techniques and applications based on detecting the position and/or rotation of fixed magnets with respect to a magnetometer or similar sensor.

In one of the earliest systems to exploit magnets, Abracadabra [7] demonstrated how a small permanent magnet could expand the input space of a wristwatch computer. A ring-shaped magnet was worn on a user's finger and tracked by a magnetometer embedded in the watch in order to determine its relative position. This data was used to control a cursor, make selections and issue basic gestures. Other authors have extended this basic concept. For example, Ketabdar et al.'s Magnetic signature [14] and MagiWrite [15] track magnets on fingers to allow smartphone users to write their signature or input numbers by gesturing in the space around a mobile device. Similarly MagiMusic [13] allows users to strum a virtual guitar by swinging a magnetic ring around their mobile.

Researchers have also explored the possibilities of mounting magnetic sensors on fingers. FingerPad [4], for example, uses a grid of hall-effect sensors on the nail of a user's index finger and a magnet on the thumbnail. With this setup subtle and private finger gestures, such as pinching, or writing numbers with the thumb, can be

effectively tracked. Chen et al.'s uTrack [6] achieves a similar goal by requiring users to wear a pair of three-axial magnetometers on their fingers and a permanent magnet on their thumb. Software processes the resultant sensor data to provide a measure of continuous relative thumb position that can be used for pointing or gesturing in a 3D space.

Embedding magnets into peripherals or tokens offers the potential to track these items as part of an interactive system. MagPen [9] demonstrates how interaction with a capacitive stylus on a tablet touchscreen can be augmented with an embedded fixed magnet. Using the in-device magnetometer, the system supports sensing the orientation of the pen, the identity (or type) of the pen, pen gestures such as flipping and the pressure exerted against the screen during drawing. GaussSense [19], a magnetic sensor grid based on 512 hall-effect sensors, can also be used to track a fixed magnet within a pen to report stylus tip location, height, pressure and angle. Although complex, the GaussSense sensing system is slim and can be placed behind any screen or surface to create a drawable display.

Magnetic systems can also be used to track other forms of input device. Bianchi and Oakley's Magnetic Accessories [3], for example, show how a mobile device magnetometer can sense fixed magnets attached to a range of physical objects, such as cubes, sliders or dials, to detect meaningful physical manipulations such as flipping, moving or spinning. A substantial limitation to this work is that only a single physical control can be tracked at any one time. Various techniques have been proposed to sidestep this issue and support simultaneous tracking of multiple objects. MagGetz [8] fixes the locations of a small set of controls around a device (e.g. two sliders and one button) and trains a machine learning classifier to disambiguate simultaneous or overlapping one-dimensional changes to these widget positions. While elegant, this approach cannot track large scale or unconstrained movements and is limited in the number of items it can distinguish. GaussBits [18] and GaussBricks [17], based on the powerful and expressive GaussSense system [19], use the sensor grid to track the position, rotation and orientation of multiple magnetic objects simultaneously. This supports a rich set of interactions based on unconstrained movements of objects over the sensor surface. While large numbers of objects can be tracked, the system relies on complex bespoke hardware and, in contrast to the volumes of sensing space available in other magnetic systems, works only when objects are positioned directly over the top of the sensor surface.

MAGNID SYSTEM OVERVIEW

The MagnID system adopts the novel approach of designing active magnetic tokens with the goal of supporting detection of relatively unconstrained movements of multiple objects in the area around a single standard magnetometer. All models, schematics, part lists and source code are available online at <https://github.com/makinteract/MagnID>.

MagnID is composed of a set of eight custom tokens, a standard sensor and a software recognition system. Each token spins a magnet around the axis perpendicular to its magnetic flux at a carefully selected unique frequency. By doing so, the tokens systematically flip the polarity of their magnetic fields in sinusoidal temporal patterns (Figure 1). The sensor, a triaxial magnetometer, detects the cumulative magnetic field generated by multiple tokens on each of its three sensor axis. The software system applies a series of bandpass filters to this data to recover signals from the individual tokens. This enables us to determine the presence or absence of the different tokens. Furthermore, by extracting the power within each frequency band, we are also able to infer the distance between each token and the sensor on each axis. Using this distance data, we can determine the spatial position of each token with respect to a set of previously calibrated locations, or linearly interpolate token position between two previously calibrated points to get a more fine-grained measurement. In summary, MagnID innovates over prior work by creating a novel magnetic token system with this set of properties:

Multiple tokens: MagnID supports use of up to eight simultaneous tokens, similar to tangible platforms based on other sensing systems such as Lumino [2] or Siftables [20].

Multiple locations: Movements are relatively unconstrained - each token can be freely placed and detected in a large set of possible locations.

Sensing Area: MagnID tokens can be tracked both over the surface of a mobile device and in the “around-device” interaction space (10-20 cm around a mobile) [16].

Commodity sensor: MagnID tokens are sensed by a single triaxial magnetometer, a common component in most smart mobile devices [8].

Tokens and Sensor Unit

Each MagnID token (see Figure 2) consists of a plastic housing designed in SolidWorks and printed with PLA on an Ultimaker 3D printer. Mounted on top of this unit are a sheet of colored card and a 5mm thick layer of Plexiglas with engraved token icons. Rubber feet insulate the token from the surface it is situated on. The final dimensions are 50mm by 50mm by 40mm high and each token weighs 67 grams when assembled. Each token contains a single Neodymium 7mm diameter x 3mm depth 3T disc-shaped permanent magnet, attached via a 3D printed mount to an upwards facing 3V DC motor. The motor is situated in the center of the token and spins the magnet perpendicularly to its magnetic axis (Figure 1), resulting in rotation invariant tokens. The motor is inexpensive, small, and features low power consumption (50 mA), low noise (48 dB), a small reduction ratio (1/5.14), a low stall current (<200mA) and a maximum speed of 6420 RPM. These features allow it to spin the magnet at frequencies between 5Hz and 100 Hz. The motor is connected to a 100Ω variable resistor that can

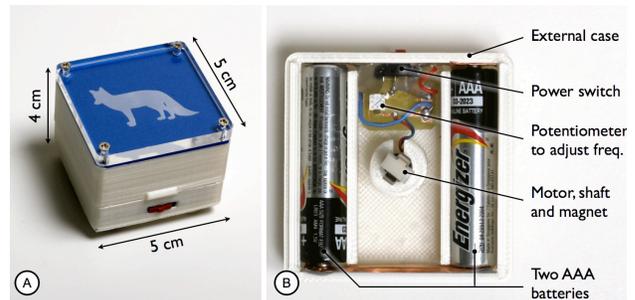


Figure 2. Outside (A) and inside (B) view of token hardware.

adjust the current and therefore the spinning frequency. Using this setup, in the current version of MagnID, eight tokens were created and set to spin at frequencies of 7.5Hz, 12.5Hz, 17.5Hz, 22.5Hz, 27.5Hz, 32.5Hz, 37.5Hz, and 42.5Hz.

MagnID tokens are powered by two AAA batteries connected in series that support up to 24 hours of continuous usage. Early tests showed that tokens with this simple design produced highly consistent (e.g. $\pm 1\text{Hz}$) rotation frequencies for periods in excess of two hours, more than sufficient for application development and test purposes. Finally, the tokens feature a switch that toggles the unit on and off. All components were mounted on a custom PCB. These design choices offer flexibility in terms of the rotational frequencies we can generate as well as simplicity, reliability and cost-effectiveness. The total price for a single MagnID token is under ten USD: motor (4\$), batteries (2\$), magnet (0.1\$), electronic components (1\$) and housing (2\$). Furthermore, after materials have been gathered and produced, token assembly is a simple task requiring approximately 30 minutes. These choices enabled production of a large token set for application development.

For development purposes, we also constructed a sensor prototype using an external magnetometer unit connected to a PC. This is because our software system requires libraries and tools that are not currently available for mobile platforms (see limitation section). However, to ensure compatibility with current mobile devices, our sensing system was based on a cheap, commercially available triaxial magnetometer (Honeywell HMC5883L, available for under 2 USD) capable of a sample rate of 100 Hz (and therefore able to detect spinning magnetic fields at frequencies up to 50Hz). We connected this device directly to an Arduino Uno and, via a USB based 115200 baud RS232 link, to the host PC that then executed all signal processing and the location detection algorithm.

Software Implementation

The MagnID software consists of a configuration and calibration interface, a sensing and filtering system, a message broadcasting system. All software was written in Java and runs on a desktop computer.

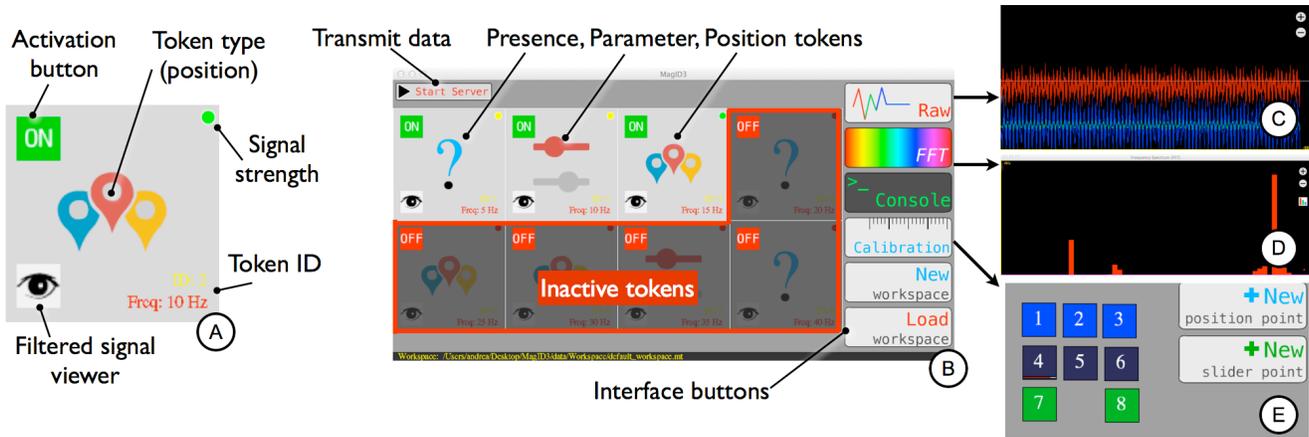


Figure 3. The main software interface (B) is composed by eight identical interface elements representing frequency bands and their parameters (A). Users can customize the token type, and activate/deactivate the frequency band. Tools for displaying the raw three-axial signal (C), the frequency spectrum (D), or for calibrating tokens (E) are also available from the main interface.

Calibration and Configuration: User interface

To use MagnID an application developer must first calibrate and configure the tokens they will use. MagnID provides an interactive application to support these activities. The main interface (Figure 3.B) shows the eight possible MagnID tokens, each with its own unique spinning frequency and ID. The frequencies used match those of the token set (but are labeled at the lower bound of a 5Hz window around the token frequency, e.g. 5Hz for a token frequency of 7.5 Hz, see Figure 3). Users can click to activate/deactivate tokens and select the recognition type from among three possible options: presence, position, or parameter. Setting a token as presence means that its state will be reported by the MagnID system as binary - data will be returned simply indicating whether or not the token is detected. Tokens configured as position return not only presence, but also location information from a set of pre-calibrated options. Finally, parameter tokens return a more fine-grained measure of location derived from a linear interpolation between two or more pre-calibrated locations.

The location calibration process also takes place in this application (Figure 3.E). This is done on a separate screen in which users can add and position calibration points, shown as colored boxes, in a 2D space. Each calibration point represents categorical data, and the spatial arrangement is solely used as a planning or mnemonic technique for users. After a layout is complete, clicking on a calibration point starts a data capture process. This involves physically positioning a MagnID token in a desired real-world location and then logging one second of data from the system magnetometer (100 samples). This data is then associated with the calibration point. This process is repeated for each remaining calibration point and the final data logs are stored in a single calibration file that can be loaded at runtime by a MagnID application. The calibration process can be performed with just one MagnID token (and generalized to the whole set) as the power of the

magnetic field generated by each token is identical - only the frequency varies between the tokens.

The configuration system also contains visualization and debug tools (Figure 3.C and D). Users can toggle the server message broadcast and open a console to examine the broadcasted messages. Furthermore, they can view the filtered data for each token, a quick and effective way to see if the tokens are visible to the system and gauge the power of the signal being measured. The interface also supports viewing the raw sensor data and the frequency spectrum of the aggregate signal. This is a useful way to view, debug or fine tune token frequencies.

Sensing and token location detection

The filtering algorithms operate on the raw triaxial magnetic field data sampled by the sensing hardware at 100 Hz. Eight frequency bands are used (one for each MagnID token) each spanning five Hz and centered on the MagnID token frequencies (e.g. 5Hz-10Hz, 10Hz-15Hz, 15Hz-20Hz, etc.). Using the Matlab Filter Design and Analysis toolkit we produced FIR bandpass filters using either the Equiripple method or a Hamming window (order 100) for each of these eight bands. Different token types used the two different filters to optimize performance. Coefficients were stored in files and loaded in our software at run time. The filtered signal captured from each token takes the form of three independent zero-centered sinusoidal bipolar waves (one on each sensor axis) with identical frequencies but different amplitudes. The amplitudes express the distance between the token and the sensor according to the inverse cubic law [22]. Before further processing, we rectify the waves then apply a median filter to reduce noise (of size equal to the wave period). This yields a steady waveform representing the strength of the magnetic field emanating from each token.

We then process the tokens according to their recognition type. Presence tokens are processed to determine whether they are in range of the sensor by comparing the overall

power in the frequency band against a user configurable threshold value. For position tokens, the aggregate magnitude (for each axis of sensor data) is matched against the data from the calibration points using a Support Vector Machine (SVM). Finally, data from parameter tokens is analyzed using linear regression to interpolate between two or more pre-calibrated locations in order to infer the tokens relative position with respect to these points.

Broadcasting Token Events

After determining the presence, position or parameters of the tokens around the sensor, the MagnID software system broadcasts this data at a user-configurable rate using the OSC protocol. The application is configured as a server and simply sends packets in real time to an IP broadcast address, a technique that is also used in the popular TUIO toolkit [12]. Each broadcast packet contains the token type (presence, position or parameter), the token ID (or frequency band), the filtered triaxial magnetometer readings and, in the case of position and parameter tokens, the categorical or interpolated token location. To listen in to this data, a client application needs simply to capture packets sent to the broadcast IP address, avoiding the need to integrate computationally intensive signal processing code into end-user applications.

EVALUATION

MagnID tracks tokens based on their distance from the sensor unit. As such, token tracking performance may be influenced by the number of locations considered and the spacing between them. Generally, accuracy can be expected to drop when the number of locations and/or their spatial density goes up. Furthermore, the distance between locations and the sensor can also impact performance - tokens at very short ranges lead to noisy data, while distant tokens are too faint for reliable detection. However, the system should be robust to increasing numbers of simultaneously active tokens and also perform similarly with all tokens (e.g. across all frequency bands regardless of the band that was initially used for training the classifier). To verify system performance, particularly with regard to tracking accuracy, we constructed five typical arrangements of tokens: two in the form of rows, and three in the form of 2D grids (see Table 1). In all cases locations were immediately adjacent to each other (e.g. spaced at five

Layout	1D / 2D	Mean Token Distance (cm)	Calibration token 10-15 Hz	Test token 30-35 Hz
● ●	1	13	99.5% K=0.99	99.5% K=0.99
● ● ●	1	14	99.6% K=0.99	99.6% K=0.99
● ● ● ●	2	15	99.7% K=0.99	99.7% K=0.99
● ● ● ● ●	2	16	99.8% K=0.99	99.8% K=0.99
● ● ● ● ● ●	2	18	99.8% K=0.99	93.8% K=0.93

Table 1. Table shows accuracy for different layout. Distance is computed between the sensor and the centroid of the layout.

cm intervals, the size of the tokens). The sensor was also always located at the top right of the layout, 10 cm away from the nearest location and rotated 45° to face the grid.

For each arrangement, we trained our software with the corresponding calibration data. We used a calibration token (12.5Hz) and sampled 100 samples of filtered data per location. We then collected 100 samples of test data for each location using both the calibration token and a test token (32.5Hz). Table 1 shows the recognition results. These indicate that for all save one configuration location recognition is achieved with above 99% accuracy. In the final, and most complex configuration of nine locations, accuracy dropped to 93%. A close examination of these cases showed that approximately half of the errors involved misclassification of the top-left location as the central location. This is likely due to either the large mean distance of tokens in the layout and the sensor (18 cm) or the similar radial distance between the sensor and these two specific locations. These data suggest that for optimal accuracy, sample applications should work with two-dimensional layouts with a maximum of six different token locations.

We also recorded recognition time during this process. Tokens were recognized within one second, but localization showed greater variability. Basically, depending on factors such as distance from the sensor, the number of tokens used simultaneously and the proximity of other tokens, the time to localize a token varied by up to one additional second.

EXAMPLE APPLICATIONS

To showcase the capabilities of the MagnID system, we constructed five demonstration applications that highlight a range of interaction types, scenarios and possibilities. All applications were developed in Processing on a Samsung Galaxy Note 8.0 Android tablet and wirelessly connected to the MagnID server application to receive information about the tokens. In each case, the MagnID sensor unit was placed near the tablet (the exact position varied according to the desired token arrangement) during calibration and application use. The applications are described below, organized according to the token features they deploy.

Token Presence: We constructed a playful application that associates content shown on a tablet with the placement and removal of physical tokens around a device (Figure 4). The context was animals appearing and disappearing from a zoo cage. In the application, two cages are shown - one on the tablet screen and one on an adjacent paper game board. By placing a lion, elephant or other animal token on top of the



Figure 4. Token presence application. If there is no token in the physical cage (A), the virtual cage is empty as well. If token are present (B, C), the application detects them.

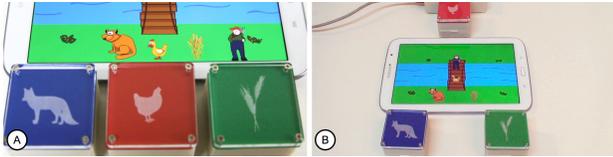


Figure 5. The tokens for a fox, chicken and grain (A) are moved and the system independently tracks their location (B).

paper cage, a virtual icon showing this animal appears on-screen. Removal of the token leads to the disappearance of the animal. Up to five animals can share the cage simultaneously, creating a playful and attractive on-screen scene that directly reflects the tokens that are present on the paper game board.

Token Position: Independently detecting the absolute and/or relative positions of multiple tokens is a fundamental enabling feature of tangible systems [24]. Accordingly, we developed three applications that take advantage of MagnID’s ability to independently detect the position of multiple tokens. In the first, shown in Figure 5, we developed a simple game based on the riddle of farmer who needs transport a fox, a chicken and a sack of grain across a river. Only one item can be moved at once and, if left alone, the fox will eat the chicken and the chicken the grain. In the game, each commodity is represented by a token and an on-screen icons, initially clustered on one side of the river (in the case of icons) and tablet (in the case of the tokens). Users can move a token to the other side of the tablet to instruct the on-screen farmer to move the appropriate item across the river. Simple game logic maintains the state of the system and informs users when they win or lose. In this application three tokens are simultaneously and accurately tracked between six valid positions.

The second position related application is based on the scenario of language learning and tracks a larger number of tokens and locations (Figure 6). The tablet screen shows four locations labeled by flags, each representing a different nation and language. Different animal tokens (e.g. elephant, fox) can be placed on each on-screen box and then tapping on the associated flag triggers a audio sample in which a native speaker states the animal’s name in the appropriate language. For example, placing the fox token on the Portuguese game board flag, then tapping the on-screen icon will play “raposa”, the Portuguese for fox. This application extends the previous position-tracking demo in two ways. Firstly, it showcases a larger number of tokens and locations - any of six animals can be placed on any of four language flags. Secondly, it shows the possibility of

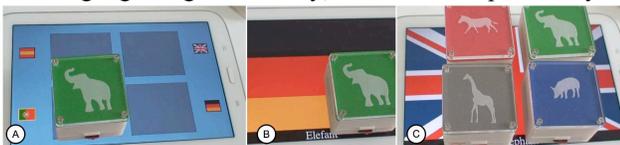


Figure 6. Tracking multiple tokens in multiple locations: tokens representing animals and located on flag-labelled boxes trigger the animal’s name in the appropriate language.



Figure 7. In this LOGO-like application, the system detects different sequences of tokens and uses them to instruct a turtle how to move (draw) on the screen.

using tokens on top of a mobile device and in combination with traditional on-screen activities such as tapping and selecting. This showcases a rich interaction space merging tangible tokens with traditional graphical input.

The final position based application implements a simple LOGO inspired turtle [21]. Eight tokens are used, representing instructions that control the movement and rotation of a turtle icon shown on the tablet screen (Figure 7). Three tokens represent movements of different amounts (small, medium and large) and five tokens represent rotations (between 9 and 155 degrees, selected to allow a rich range of shapes). Up to four of these commands can be arranged in a row adjacent to the tablet at any one time. Then, by tapping the screen, the turtle commences to execute the commands in a loop - the leftmost command first and the rightmost last. By arranging the commands in different sequences a wide range of shapes including squares, circles, triangles, and stars can be produced programmatically. This application moves beyond the prior demonstrations by showing the ability to infer and respond to relative position - eight tokens can be freely arranged in any of four locations and the order in which they are arranged can be determined.

Token Parameter: The final application showcases the ability of MagnID to detect token state beyond categorical positions (Figure 8). It is a stylus based paint application for a tablet with tangible controls in the form of two tokens located to one side of the device. The position of each token controls a different quality of the pen - one its color, the other its brush size. Control is achieved by moving the tokens to the left and right (like a one dimensional slider) and each token supports an analogue interpolation of its position along a predetermined movement range. Furthermore, both tokens can be operated independently and simultaneously. Basically, this setup allows a user to paint with the pen in their dominant hand and make fine-grained adjustments to the color and size of their strokes using the two tokens. This application showcases the

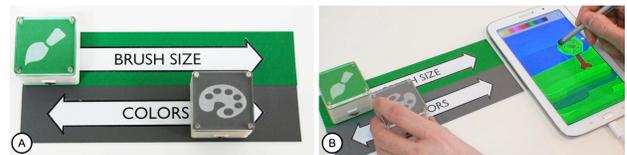


Figure 8. Two tokens are used as sliders to control the brush size and the color (A), in a drawing application (B).

sensitivity of the parameter tokens in MagnID and the ability to reliably interpolate between two positions given pre-calibrated locations.

DISCUSSION

There are a number of limitations to the current MagnID system. Although magnetism is immune to many of the field of view problems that affect optical tracking systems, its range is relatively limited. With the current 7mm magnets and magnetometer, tokens can be reliably recognized in the range of between 3cm and 25cm from the sensor. The use of stronger magnets would boost the maximum range at the cost of increasingly noisy data at close range. One potential solution to this problem may be to base future versions of the system on two magnetometers, each optimally sensitive to magnetic fields of different strengths.

The tracking system used in MagnID, fundamentally based on detecting the distance between tokens and the sensor also imposes some limits in terms of the arrangements of locations that are supported. Basically, while the system is sufficiently accurate to detect tokens arranged in common structures such as rows or simple grids, more complex structures (e.g. Table 1, final row) result in locations that are hard to distinguish from one another. Application designers using the MagnID approach will have to carefully select the token locations used in their systems to optimize their distinguishability.

There are also several issues with the tokens physical design. Firstly, although the current hardware prototypes are equivalently sized to the tokens in many tangible systems (five by five cm, similar to Siftables [20]) the limited sensing range available restricts interaction to approximately 25 unique locations in the area immediately around the sensor. This issue could be partly addressed through miniaturizing the tokens. Secondly, the tokens are based on mechanical movement and thus emit low-level noise and vibrations. Measured in a quiet room (40-45dB ambient), a microphone placed 10 cm away from a MagnID tokens registers between 50 dB for low frequencies and 70 dB for high frequencies, an audible level of noise. One potential solution to this problem is to develop non-mechanical solutions based on electromagnets powered in timer controlled oscillating patterns (PWM). A disadvantage to this purely digital approach would likely be substantially greater power consumption.

The software systems also suffer from a number of limitations. Although this paper makes a case for MagnID as an effective tool to expand the interaction potential of mobile devices through physical tokens, our system prototype does not currently natively run on a mobile platform. Instead, a custom sensor is connected to a desktop computer as this approach simplifies sensing and data processing. However, we argue this issue does not detract from the main objective of this paper - to show the

feasibility of the MagnID system independently of the computational platform it is based on. Furthermore, in order to test the feasibility of a fully mobile approach, we ported the sensing system to the mobile device (Samsung Galaxy Note 8.0) used to develop the demonstration applications. We used the on-board magnetometer to capture signals at 100Hz and streamed them over the Android Debug Bridge (ADB) on USB to a PC running the MagnID software. Initial tests show the on-board sensor (a Yamaha MS-3R YAS532) is capable of analogous frequency recognition to our dedicated sensor unit. However, sensitivity was reduced - the effective sensing range around the device was reduced from 25 cm to approximately 10 cm. Future work will rectify this problem by integrating stronger magnets into the system, or seeking a mobile device that features a magnetometer than is configured for high sensitivity applications (such hardware settings are not typically made available to developers on standard Android devices).

CONCLUSIONS

Tangible computing is a compelling and promising interaction paradigm [23, 24] that faces many challenges before it can be adopted in mainstream commercial products. One of these relates to the demanding hardware requirements of both current research systems [e.g. 1, 2] and existing product offerings [e.g. 11]. The work in this paper contributes to a growing body of literature that addresses this problem by exploring how the sensing capabilities of existing mobile computers can be leveraged to create physical, tangible interfaces [3, 5, 25].

Fixed magnets - cheap, small and portable - have been previously proposed in order to achieve this objective. The magnetic interaction system introduced in this paper moves beyond this prior work by constructing simple, active tokens that can be independently detected. This allows us to consider a greater range of interaction scenarios than those based on a single magnet (e.g. the fingertip cursor control in Abracadabra [7], Hwang et al.'s MagPen [9] or the magnetic widgets proposed by Bianchi and Oakley [3]) or the highly constrained movement of two to three magnets [8]. Indeed, the ability to detect the location of multiple independent tokens or objects is a defining aspect of many typical tangible systems [24], and it is this functionality that our system seeks to enable.

Furthermore, unlike prior systems capable of detecting multiple magnets [17, 18], the work in this paper achieves this objective using only a single triaxial magnetometer - a standard piece of equipment in most current mobile devices. This contrasts strongly with the approaches of other magnetic sensing systems capable of tracking multiple objects. For example, the rich interactions that the impressive Gaussbits system can achieve are enabled by a large, expensive array of 768 independent sensors [18]. While the Gaussbits prototype affords many opportunities for exploring interaction scenarios [17], its bulk, cost and complexity make it an unlikely candidate for integration

into real mobile device products. Moreover, Gaussbits tokens can only be sensed if positioned on, or immediately over, the screen while MagnID's approach allows application designers to take advantage of the full volume of space around a device.

In conclusion, the goal of this paper is to create and document a magnetic tracking system that supports multiple tokens that can be freely positioned in multiple locations in the area on and around a tablet and requires only commodity sensors already integrated into smart devices. MagnID achieves these objectives and we argue this combination of functionality opens the door for a new class of tangible interfaces designed expressly for current mobile devices. We hope the availability of the MagnID platform will inspire and enable application designers and developers to create a new generation of tangible interfaces targeted towards everyday consumers.

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