MagPen: A Novel Way of Digitizing Notes Using Magnets

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ABSTRACT
This paper presents a novel method of digitizing notes and/or diagrams that are drawn on a sheet of paper. Most modern phones contain magnetometers that output the strength of the surrounding magnetic field in the x, y, and z direction. If a magnet is brought closer to the device (and the magnetometer), the values from the magnetometer will be altered. By determining the change in the altered magnetic field, we can determine the position of the magnet. With the position, we can determine the location of the magnet relative to the phone. We have created a magnet based pen (MagPen) and built an android application that allows users to write notes on a sheet of paper while their mobile phone automatically digitizes. Users will also be able to perform certain actions using the button on the pen and select various pen attributes using the MagPen.

Keywords
Pen input, magnetometer, mobile devices, notes

ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: User Interfaces: Input Devices and Strategies.

INTRODUCTION
A mobile device has a multitude of sensors ranging from GPS to a barometer. One sensor that is used daily is the capacitive sensor. Capacitive sensors detect anything that is conductive and they are used for touch input in mobile phones. We rely tremendously on touch input to interact with our devices ranging from playing games to checking notifications. We also have the ability to use our finger or styluses to write notes directly on a mobile device. However, touch/stylus input on mobile devices has its own set of problems. We are unable to easily draw detailed diagrams or write notes using the touch screen.

Is there another way to provide a different method of digitizing notes with a mobile device that expands the capabilities of touch? Another sensor that can be used for alternative methods of interaction is a magnetometer. The magnetometer senses changes in the magnetic field in all three axes (x,y,z) [10]. If the magnetic field can be detected, then it is possible to alter the magnetic field by using an external magnet. When the external magnet is moved around, it will alter the magnetic field thus producing different (x,y,z) values.

MagPen is a system that allows the user to digitize notes while they are written on a sheet of paper. The pen itself contains magnets or it can be an electromagnet. As the pen moves around in the area next to the phone, the changes in the magnetic field are detected and they are mapped out onto an x-y plane. To simulate an actual pen, the pen will only emit a magnetic field when the tip is pressed down. That allows the phone to only recognize actual pen inputs and not the pen movements.

To enable a richer set of interactions, the magnetic field strength can be used to control various pen attributes, such as stroke size or color. This is accomplished by moving the magnet based pen closer and further away to control the size of color.

There has been existing work in the industry that attempts to solve this problem. A few examples are Livescribe, Equil JOT, or the Wacom Tablets. This devices however require additional devices and/or special pen and paper to be able to digitize these notes. MagPen attempts to remove the need of additional devices by just requiring your mobile device and a custom pen.

RELATED WORKS
This project spans across multiple different fields, tangible interactions, magnet based interactions, drawing with everyday objects, and pens & touch. We have taken ideas from existing research in these areas and integrated them into MagPen.

Tangible Interaction
MagPen overall is focusing on creating alternative methods of input and interactions that use magnets embedded in real world objects. According to Tangible Bits [7], there are three concepts for tangible interaction: transforming surfaces into an active interface, coupling physical objects with digital information, and the use of ambient media with the digital world. In the context of MagPen, the real world objects can be generic (e.g. a pointing device) or embedded in other objects (e.g. pens). MagPen will make use of tangible interactions by using magnets embedded in pens or markers.

Users will be able to take notes or draw on a sheet of paper beside the phone and control pen attributes using the magnetic field strength.

The use of a magnet to draw on the screen is a complex interaction on its own but is there a way to combine touch and magnet based input (physically and mentally). TUIC looks into just this idea [15]. It allows tangible interaction directly on multi touch devices. It embeds objects with circuits that simulate touch input to allow the mobile device to detect the object. There are three methods that "TUIC" achieves this, spatial (static touch patterns), frequency (dynamic modulation of touch), and hybrid (a combination of spatial and frequency). Although this would not directly apply to MagPen since it is possible to detect magnets without touching the phone, we will be looking into how we can detect different sizes of magnets and various locations. This can be done using the magnet's intensity or frequency modulation (as described in TUIC). Frequency modulation could be used in a unique way to build custom hardware to modulate the magnetic field and detect different kinds of pens. However this will be considered as future work as per the scope of this project. In addition to detecting various pen types, we will be integrating interaction elements using a button on the pen.

"Tangible Meets Gestural" [2] mentions the value of learning and thinking is greater when using physical objects. Touching physical objects can help children learn how to count and keep track of their activities. We believe with MagPen, the value of using an actual pen will be greatly beneficial since it does not replace the user's natural way of taking notes.

Magnet-Based Interaction

Several works have investigated input methods making use of magnetometers, whether they are looking for more absolute locators mimicking a mouse or more gestural input. uTrack [5] implements an absolute locator using a magnet attached to the user's thumb and two magnetometers attached to their ring finger. The combined readings from the two sensors allow a fairly accurate location reading for the magnet. While this does show that it is possible, the implementation also highlights that a single sensor does have its limitations, especially when compromises are made such as in smartphones. Smartphone sensor reliability for augmented reality applications [4] touches on the inherent inaccuracy of cheaper sensors used in smartphones. In addition, a lot of attention is paid to how external forces can affect the readings. Improving Heading Accuracy in Smartphone-based PDR Systems using Multi-Pedestrian Sensor Fusion [1] investigates this further and attempts to improve upon the results by fusing readings from multiple sensors. In their studies, they were able to reduce the error in the heading readings by some 27% using only naive averaging, leaving room for improvement using more complex algorithms.

MagPairing [8] attempts to make use of the unique magnetic forces that a device will pick up in a given location. By tapping the phones, you move them close enough together that the magnetic fields picked up by each device are extremely similar. They are able to reliable pair devices together by encoding these readings with authentication keys and comparing similarly time stamped readings to verify the connection.

Although, these do highlight how difficult and complex it can be to make these sensors accurate enough to be used as absolute locators, there is a lot that can be done by using them in a relative sense, especially as a form of gestural input. Not only can gestures be reliably recorded, but gestures made in 3D Space are also unique to every user. If two users made box like gestures over the phone, both of their gestures would be somewhat different. This is due to users not being able to reproduce each other's gestures in 3D space within a certain threshold [13]. As we are developing this application, we need to take into account this threshold to be able to recognize certain swipe gestures across all users.

MagiMusic [10] and Magnetic Marionette [6] show that these gesture-based movements are a lot more feasible with the magnetometer than absolute inputs. MagiMusic allows digital instruments to be played by making gestures with a magnet, such as strumming a guitar. Magnetic Marionette introduces a tangible avatar attached to the device, which can be moved around to produce different facial expressions on the screen.

While the sensors in these smartphones are generally inaccurate due to compromises made in the devices manufacturing and the effect of external magnetic forces, they can be made to be more accurate in a fixed setting. If you know the ambient forces you can account for them in order to pick out the desired readings. In Pulse [14] for example, a system is designed through which the device can receive and decode a signal sent out as magnetic forces, and can even reach transfer speeds up to 44 bps. Due to the nature of the sensors used, it is an especially short-range communication method. A Sensor Fusion Method for Smart phone Orientation Estimation [3] also provides methods to work around the inherent issues with these sensors by fusing data from multiple sensors for correction. Although the final implementation here is beyond this project, much of specifics are a good base for filtering some of the sensor data. For example the low-pass filter used to smooth the readings will prove important in MagPen, and adjustments to reference frames are something that very well may come into play.

Drawing with Everyday Objects

The android application in MagPen relies on detecting changes in the magnetic field with external magnets. However, instead of just using magnets, we will be embedding the magnets in pens to allow the user to have a more natural interaction with the application. I/O Brush [11] is similar idea, it is a drawing tool aimed at young children to be able to draw with everyday objects. The authors of I/O brush built a device that molded its everyday object as a brush so users can easily create the mental mappings and seamlessly work with the everyday objects.

BlowBrush [12] is another idea that looks into tangible painting systems using a windmill. A user can blow on the windmill to paint leaves or other objects on screen. BlowBrush used this criteria to analyze and study the effectiveness of their application. This criteria is consisted of: metaphorical affordance, enjoyable engagement, tangible manipulation, spatial interaction, embodied facilitation, and expressive representation. As we are developing this application, we need to look into the criteria that BlowBrush used to analyze their own system. We especially need to evaluate the tangible and spatial interactions of our system, so that the use of the pen around the device is as intuitive and frustration-free as possible.

Pens and Touch

Pens and Touch focuses on pen based interactions with devices that have touch capabilities. This can include augmenting touch with a stylus/pen or replacing touch completely. “Pen + Touch” aims to augment touch with the capabilities and benefits of using a pen [9]. The pen is relatively more accurate, has a small area of occlusion, and provides a natural way of interacting with objects. Although MagPen does not aim to augment touch completely, it contains the ability to combine touch and pen input. For example, as MagPen is recording the pen input, the user can make annotations directly on the screen using touch. We believe there is a larger opportunity here to combine pen and touch input.

Another paper also called “MagPen” (unknown to us at the time of our app’s creation) looked into pen interaction directly on or around smartphones [6]. It combined a stylus and a magnet to allow touchscreen input while controlling various attributes of the pen. One interesting concept that was implemented was changing the brush stroke size based on the magnetic strength. As the magnet in the pen moved closer the brush stroke size became larger. Also as the magnetic field strength changed, the stroke color options also changed. We will be implementing a similar functionality however the stroke size and color will need to be explicitly set and cannot be automatically detected. This is due to the fact that the user will be writing with the pen thus moving it around the phone. The magnetic field strength will change as the user moves the pen around the phone. Therefore this value will need to be explicitly set from a menu option. This also allows the user to set these attributes as they wish rather than having set attributes for certain pens.

IMPLEMENTATION

MagPen is composed of two main areas, the hardware and the software. The hardware consists of a Pen/Electromagnet and the software consists of an Android application with various algorithms to map the magnetometer values onto an x-y plane.

- Hardware: Pen/Electromagnet
- Software: Android Application
    - Magnetometer Sensor Research
    - Selection of Various Pen Attributes

Hardware

Early on in the project, we simply used a strong magnet to understand the magnetometer readings and the various magnetic fields. Once we got a strong hold on the magnetometer, we were able to conduct research into electromagnets. The use of electromagnets is necessary in this project to allow the magnetic field to turn “on” and “off”. This enables us to detect when the pen is actually writing and when it is hovering in the air.

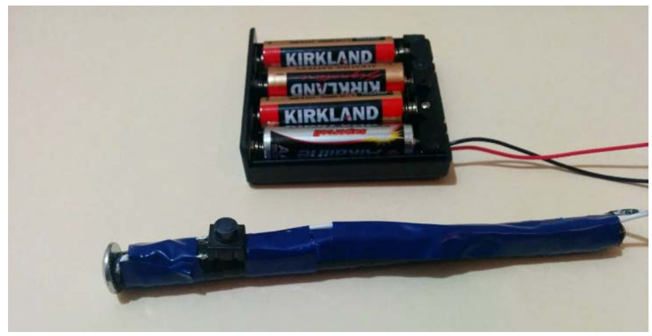

Figure 1. An electromagnet shaped like a pen

Although we were unable to integrate this with a pen, we were able to create an electromagnet in the shape of a pen. This pen consists of a long rod with wires coiled around it, essentially an electromagnet. Additional research went into this to determine what kind of electromagnet would work best. Should we use a long/short rod, bare/insulated wire, and should the battery have higher/lower voltage? From our findings, using a long rod, with larger battery voltage produces the strongest magnetic field. The stronger the magnetic field, the stronger the readings of the magnetometer. The type of wire (bare or insulated) did not have any effect on the strength of the magnetic field.

Figure 2. Push button to turn the electromagnet on or off

Since we were unable to integrate this into an actual pen, we could not successfully detect when the tip was pressed down. Therefore to simulate the interaction of the tip pressed down, a button was added on the pen. This button connects the entire circuit together thus allowing a magnetic field to be emitted. The MagPen application can detect when the button is clicked or double clicked and execute an action. Future work would include detecting when the tip has been pressed down and using those readings for the pen input. Thus freeing the button on the pen to be mapped to other actions such as start or stop recording audio.

Click Detection

As stated before, it is possible to detect a single click or double click by monitoring the magnetic sensor readings. Currently only double click is enabled in the application as it proves output lower amount of false positives. The algorithm takes in a list of magnetometer readings (e.g. last 10 readings) and calculates the differences between the values. Normally, if a user is not clicking anything, there should be minimal difference in the values (all between -3 and 3). However when the user clicks the pen, the pen will emit a magnetic field for a few seconds. Therefore, there will be a quick jump up in the magnetometer readings and a drop in magnetometer readings after a few seconds. We can detect this by checking for any jumps in the readings.

To detect double click, we detect a baseline value below a certain threshold, a jump in the values, a baseline, a jump again in the values and a baseline. To detect a single click, we check for a baseline value, a jump in the values and a baseline again. However, detecting single click had a larger amount of false positives. The algorithm detected the pen moving away as a single click. Therefore currently only double click is enabled in the application.

Software

The android application allows the user to create, view, and save documents. There is also the option to view raw magnetometer sensor readings and change application settings (e.g the algorithm).

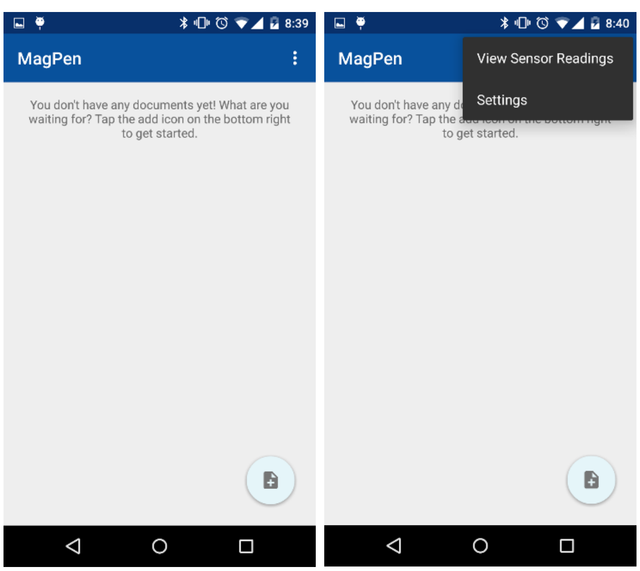

Figure 3. The main screen of the application

The sensor readings screen will display the raw magnetometer values in the x,y,z planes as well as intensity. These values are plotted on a continuously updating line graph (bottom left image). For debugging purposes, the user can calibrate the 4 corners to see the values mapped out on an x-y plane. Once the corners are calibrated, and the Readings option is deselected, a circle will be mapped onto an xy plane and will as the magnet is moved around.

Figure 4. Sensor readings view

In the settings screen, the user has the option to select various algorithms that map the magnetometer sensor readings onto the xy plane. These algorithms are described in detail later on in this document.

From the main screen, the user can tap the new document icon to get to the New Document Screen. Again similar to the sensors readings screen, the user will need to calibrate the 4 corners before using the magnet or magnet based pen (MagPen) as stroke inputs. This is done by tapping through the calibrate buttons on the bottom.

The user also has the ability to draw with touch along with magnets. This allows for quick annotation of the document while writing with the MagPen. To start magnet input, the user can double click on the MagPen or tap the rightmost pen icon. When pen input is enabled, the pen will turn white to display that magnetic input is being accepted. The other paint brush and color picker icon allows the user to choose the stroke size and color. This is described in more detail later on in this document as well.

The save icon will save the notes/drawings locally on the device. If needed the user can revisit the home screen to see the saved image.

Magnetometer Sensor Algorithms

This project required a heavy research component to map the magnetometer readings to an x-y plane. Three different algorithms have been implemented and are selectable from the settings menu. Before any magnetic inputs are used the pen must first be calibrated. This is done by pressing the calibration button at the bottom of the screen and following the instruction. Essentially it asks the user to place the pen at the four corners of their working surface and press the button again. This gets a reading for the magnetic field when the pen is at each corner, so the application can use these as references for locating the current position of the pen.

The first algorithm is a rather simple algorithm that uses only the 'x' and 'y' axis readings from the magnetometer. In the application we have called this 'Four Screen Corners '. This simply takes the current readings and places the 'x' value within the minimum and maximum 'x' values from the calibrated references, then does the same for the 'y' values. In order to try and compensate for inconsistent values, for example a 'y' value that is slightly higher at the bottom left than bottom right, the 'y' value is calculated using the top-left and bottom-left references, and then the top-right and bottom-right, then averages these values. The same is done for the 'x' value but using the two top references and then the two bottom ones.

The second algorithm attempts to use two dimensional trilateration in order to locate the pen in relation to the reference points. In the application this is called 'Trilateration'. This algorithm takes the difference in field strength between the current position and three of the reference points. It uses these differences as pseudo distances and acts as though a circle is formed around each of the reference points whose radius is this distance. It then calculates the intersection points of these three circles to find the current location of the pen in relation to the reference points.

The third algorithm attempts to change the frame of reference for the readings to zero out the 'z' values then projects these points onto the screen. In the application this is called 'Projection on Planes'. This algorithm creates rotation matrix which rotates the reference points around the 'z' axis such that the 'y' values of the top-left and top-right reference points are equal. It then creates another rotation matrix which rotates these new points around the 'y' axis such that the 'z' values are equal. It then takes the output from that rotation and creates a transformation matrix such that the top-left reference now sits at (0,0) and the bottom-right sits at (1,1). Finally the current readings is passed through these through matrices giving 'x' and 'y' values each in the range of [0,1]. These values are then multiplied by the width and height of the screen respectively in order to get screen coordinates.

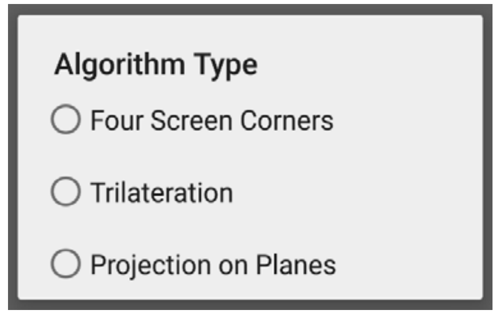

Figure 5. Mapping algorithms

Selection of Pen Attributes

The strength of the magnetic field created by the electromagnet can be used in order to set several pen attributes. Dialogs have been implemented in order to set the color and stroke size of the pen. In order to set these attributes the magnetic pen to first be calibrated. When the dialog is then opened the user can set the color or stroke width by moving the pen left and right. The dialogs have dynamic feedback to show the currently selected value and if the user confirms the selection the appropriate attribute will be set. Naturally, selecting the cancel option will cancel the dialog and keep the previously set attribute values.

The dialogs simply use the magnitude of the magnetic field strength in order to set these values, with the minimum and maximum values represented by the minimum and maximum detected during calibration respectively. Any values outside of this range will simply be clamped.

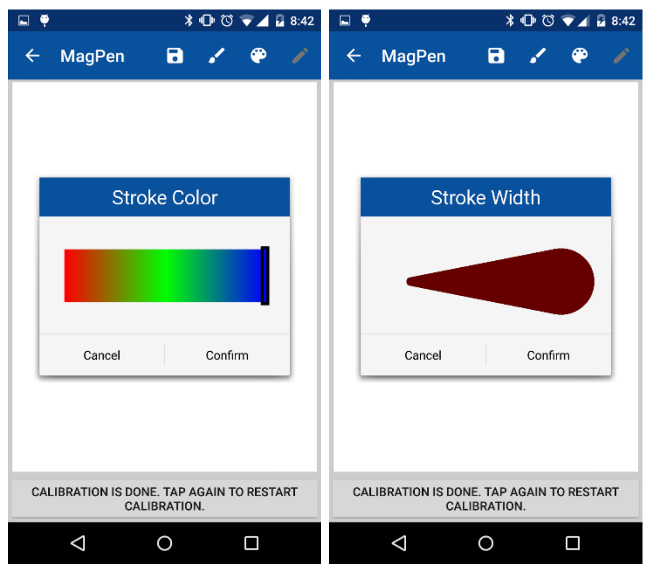

Figure 6. Stroke width and color selectors

UI CONTRIBUTION

The goal of this project was to implement a form of note digitization that would feel more natural to the user. It would allow the user to go through their usual pen and paper method of taking notes and the digitization would occur in parallel, or at least the digital method would feel like the manual one. Although not fully functional based on our original ambitions, the pseudo pen we have created can be used to draw to the screen, and feels much more natural to a user that is used to using a pen and paper. In addition we hope that the button on the side of the pen is more natural than having to physically interact with the phone and makes their workflow more fluid.

Within the application we attempted to make the interface very minimal and intuitive. Given that there are no saved documents, implying the application has not been used before, the user is given direction to press the button for a new document. The action bar for a document is limited to just a few actions and we hide actions that are not applicable in the current context. The button for calibration is made large to mark its importance but placed at the button to hopefully not distract a user who does not currently need it. The calibration process tells the user what to do by giving them instruction for each step on said button.

The pen icon on the new document screen is greyed out to indicate that the magnet input is not being accepted. When the user double clicks on the MagPen or enables the magnet input by tapping the icon, the pen icon will turn white indicating that the drawing is accepting magnet input.

The dialogs for setting the stroke width and color are minimal, including just a title, feedback for current selections and confirm/cancel buttons. The feedback for these dialogs is immediate so that the user clearly knows what value they have currently selected and will be set if the confirmation button is pressed. Additionally, messages are displayed upon confirmation or cancellation of the dialogs to further clarify what has occurred.

DISCUSSIONS AND LIMITATIONS

In our initial and follow-up project proposals our goal was to have the position of our magnets, or pen with an embedded magnet, be calculated such that they could be used as a two dimensional pointer on the device. The movements that the user made with this pointer would be able to be read as gestures or patterns. These could be larger gestures such as directional movements that would be mapped to actions, such as swiping left or right to move through pages, or more precise patterns such as characters that could recognized and recorded as digital notes.

However through much more in depth testing and research, it was decided that the readings from the magnetometer from our smartphones were only reliably useful in a one dimensional sense. When converted to an overall magnitude of magnetic field strength, these readings could be pretty reliably used as input in order to select from a range of values. But for several reasons their mappings to a two dimensional plane were much less reliable.

One of the biggest issues we ran into was the magnetization of the phone itself. The pen could be calibrated, but slowly the components of the phone would become slightly magnetized throwing off the readings. On a single device this could possibly be accounted for, but since different android based phones would all have different components and internal layouts there was no way to reliably account for this other than constant calibration.

Another issue is that magnetic field is not uniform. In the context of our use this meant that the magnitude of readings would ramp up considerably when the magnets align with the axis of the magnetometer. This presents a problem as we couldn't find a reliable method to distinguish between a single axis value changing due to axis alignment, or because the magnet was moves much closer to the device. This was improved by using an electromagnet with a long metal base, but could never be completely fixed. If the magnitude of the magnetic field was known or the direction was known to be static, an absolute position could be reliably calculated.

Unfortunately there were too many unknowns in what we were attempting, meaning that there were often multiple possible locations, and the correct one couldn't be reliably selected without another source of information to verify it, such as a reading from another magnetometer.

FUTURE WORK

Moving forward, the focus is on improving the mapping of the magnetometer readings to the phone screen more accurately and reliably. This would represent the biggest leap in capabilities of the system. If this was improved enough to reliably recognize symbols and/or characters we will have a system that would be able to replace other note digitizing systems that require much more preparation and outside hardware to use.

The next steps would be improvements to the limiting factors of the system. This would include finding ways to increase the usable area of the system, allowing more freedom for the user. We would also like to stabilize the magnetometer readings further and find ways to decrease the impact of outside magnetic forces. This lessen the need for the users to re-calibrate the system, and hopefully allow the system to automatically correct for the phone being magnetized. The click detection algorithm could also be improved, such that the clicks are more reliably detected with fewer false positives.

The viability of using the magnetometer alone is also still being debated. As progress is made we are always looking for ways to use other existing sensors and features of the devices to help improve the system.

To enable a richer set of interactions, certain gestures made on the sheet of paper could even be recognized on the smartphone and be linked to an action. For example, the user will need to draw a specific identifier, and draw a circle to simulate recording. Or the user could draw an identifier and draw an x to simulate delete and etc. The identifier will need to be used so the gestures will not be mixed with regular letters, numbers, and drawings.

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