GaussSense: Attachable Stylus Sensing Using Magnetic Sensor Grid

Rong-Hao Liang[*‡] **Kai-Yin Cheng**[*] **Chao-Huai Su**[*] **Chien-Ting Weng**[*]
Bing-Yu Chen[†] **De-Nian Yang**[‡]
[*†]National Taiwan University [‡]Academia Sinica
[*]{howieliang,keynes,domossu,ctweng}@cmlab.csie.ntu.edu.tw
[†]robin@ntu.edu.tw [‡]dnyang@iis.sinica.edu.tw

ABSTRACT
This work presents *GaussSense*, which is a back-of-device sensing technique for enabling input on an arbitrary surface using stylus by exploiting magnetism. A 2mm-thick Hall sensor grid is developed to sense magnets that are embedded in the stylus. Our system can sense the magnetic field that is emitted from the stylus when it is within 2cm of any non-ferromagnetic surface. Attaching the sensor behind an arbitrary thin surface enables the stylus input to be recognized by analyzing the distribution of the applied magnetic field. Attaching the sensor grid to the back of a touchscreen device and incorporating magnets into the corresponding stylus enable the system 1) to distinguish touch events that are caused by a finger from those caused by the stylus, 2) to sense the tilt angle of the stylus and the pressure with which it is applied, and 3) to detect where the stylus hovers over the screen. A pilot study reveals that people were satisfied with the novel sketching experiences based on this system.

Author Keywords
Magnetism; Stylus; Sensor; Touchscreen.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

General Terms
Design; Measurement; Experimentation.

INTRODUCTION

Stylus input is becoming increasingly prevalent, as people increasingly rely on mobile devices in everyday applications, such as taking notes. To improve the support of these devices for the use of stylus without deploying external optical detectors as shown in Figure 1(a), some manufacturers have started to integrate an additional stylus sensor into devices tightly with the overlain touch panel (Figure 1(b)) or behind

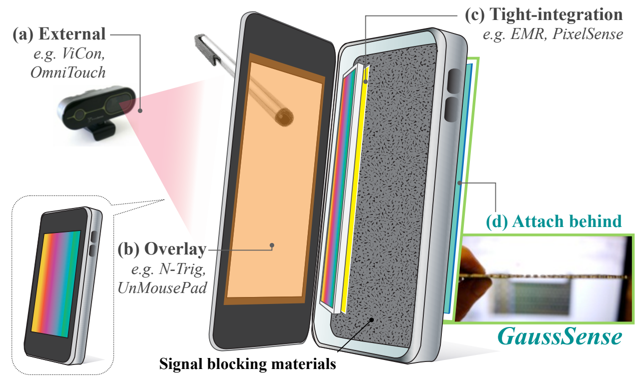


Figure 1. Unlike conventional stylus sensors, the *GaussSense* sensor can be directly attached to the back of the device as a functional extension.

the display module (Figure 1(c)). However, since such sensors may be useless through the materials of which the devices are made, they cannot simply be attached behind the devices as retrofit extensions. Some attachable stylus sensors, such as *UnMousePad* [13], can be made transparent overlay onto a back-lit display, but the original touch input capability of the device may thus be disabled.

This paper, presents a new back-of-device stylus sensing method, *GaussSense*, which can be directly attached behind a device to enable or enhance stylus input without modifying the front surface (Figure 1(d)). The method is based on the penetrability of magnetism by a magnetic field. A 2mm-thick sensor board is developed for sensing the distribution of a magnetic field from a specially designed magnetic stylus. A user can perform a few calibration steps to enable the stylus to be sensed by the magnetic field sensor board.

The developed technology can be applied in two different manners. For arbitrary non-ferromagnetic surfaces or displays, *GaussSense* can be deployed behind to locate the magnetic stylus on the front of the device. For conventional touchscreens, it can function as an additional sensor that extends the original input capability to stylus detection, including discriminating the stylus events from the finger touch events, determining stylus' tilt angle and stylus tip's pressure, and locating the position above where the stylus hovers.

An initial working prototype made by an 8mm-diameter $\times$ 36mm-height magnetic stylus and a $60 \times 80mm^2$ sensor board with 192 analog Hall sensors in the form of a grid are implemented and evaluated. The experimental results show that the technology is effective on a non-ferromagnetic device that is under 2cm thick. Finally a sketching application is developed to evaluate the usefulness of the technology, and the results of a pilot study show that people are satisfied with the ability to sketch naturally whatever they want to sketch.

RELATED WORK

Numerous works have been carried out to add stylus detection to displays. The conventional solution is to overlay the screen with a transparent resistive- or capacitive-based panel. With respect to resistive technologies, although the Interpolated Force Sensitive Resistance (IFSR) technology [13] can be used to track a stylus, it cannot easily sense its angle of tilt or position where it hovers. Capacitive technologies [3] allow zero-force manipulation, meaning that the stylus' pressure [18], angle [12] and location of hover [11] can be approximately estimated, but they cannot reliably distinguish between a finger tip event and a stylus tip event.

Another common approach involves external cameras (Figure 1(a)) to capture stylus operations [7] or to assist other stylus input methods to identify subtle operations, such as rolling a stylus [2]. A cuboid stylus, like *Conté* [16], can be used to ease mode switching. However, external detectors are usually not very portable. *OmniTouch* [5] is an exception: it uses a shoulder-worn depth camera that supports multi-touch applications on everyday surfaces with stylus inputs enabled. However, the precision and performance of this system may not suffice for writing or drawing applications, including note-taking and sketching.

With respect to mobility, integrating an additional stylus sensor closely with the overlain touch panel (Figure 1(b)) or behind a display module (Figure 1(c)), as is done with N-Trig DuoSense [9] and electromagnetic resonance[1] (EMR) sensors, respectively, enables advanced stylus detection on a traditional touchscreen. *PixelSense*[2] integrates infrared sensors into every pixel to eliminate external calibrations. These sensing technologies must be tightly integrated with display modules: they cannot be loosely attached behind a device because the physical materials of which the device is made would block signals.

To develop a sensing technology that can be attached to the back of a device as shown in Figure 1(d), the exploitation of directional magnetism is promising because magnetic fields can penetrate most physical materials. *Polhemus*[3] can be used to perform high-resolution tracking by exploiting a strongly penetrating electromagnetic field, but the tracking mechanism requires a heavy external emitter. Ferromagnetic input device deploys an array of coils [8] can be used to sense free-form ferromagnetic objects, but its mobility is constrained by the size of the device. Magnetometers are embedded in most smartphones, but its radial detection range suggests remapping of the input space [1, 6]. The Hall sensor is another widely used magnetic field sensor. It is tiny, inexpensive and consumes low power. *SmartTable* [14] has successfully demonstrated that deploying Hall sensors in a grid can provide 2D detection, but this method is not sufficiently precise for detecting operations with a stylus.

[1]http://www.wacom.com

[2]http://www.microsoft.com/surface/

[3]http://www.polhemus.com/

DESIGN

Hardware

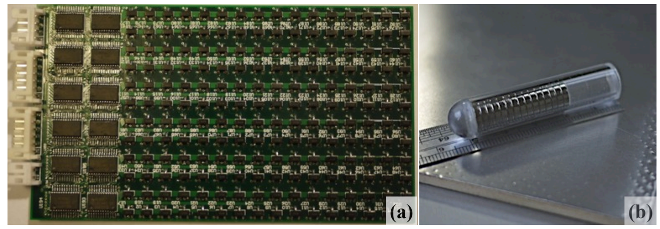


Figure 2. (a) Sensor board with 192 Hall-effect sensors and 12 multiplexers. (b) Magnetic stylus above the example aluminum-coated surface.

The goal of this work is to build an attachable, lightweight sensor system that can detect a magnetic field that penetrates from the opposite side of the device to which it is attached. A 2mm-thick sensor board of dimensions 60(W) $\times$ 80(H) mm^2 is made from 12 $\times$ 16 = 192 Winson WSH138 Hall sensors[4] that are arranged in a grid. Each sensor element is designed to provide N-polar detection linearly in the range of 0 to 200 Gauss on a 512-point scale. All sensor data are multiplexed and transferred to a PC through a Teensy 2.0 microcontroller[5] via USB connection. The captured data are upsampled using the bi-cubic interpolation method (or the bilinear interpolation method for the sensors at the boundaries) to 352 $\times$ 480 (163 dpi), consistently above 60 fps.

A prototype magnetic stylus, in which is embedded an 8mm-diameter $\times$ 30mm-height stack of cylindrical neodymium magnets in a 6mm-radius acrylic pipe, and which has an acrylic hemisphere as its tip, is built.

Signal Processing

Calibration: To eliminate the zero-biasing problem of each sensor element i, a default value v for each element is set by averaging the initial values v_i, while the sensor is turned on, and then calibrating the values of each element at runtime by adding a pre-computed offset between v and v_i.

Sensing: After collecting calibrated raw values v'_i of the sensors, the intensity I_i of each sampling point i is calculated by $I_i = c v'^{\gamma}_i$, where c is a constant and γ is a correction factor. For cylindrical magnets used in the stylus, the γ is set to 0.5 because the sensed intensity of the magnetic field is inverse-cubically related to the vertical distance from sensor to dipole [17]. Thereafter, I_i is utilized to reconstruct the shape of magnetic field exerted from the stylus. The steps of signal processing are listed below:

1. Interpolate the raw data to construct the magnetic field image (Figure 3(a)), and define the global maximum intensity I_{max} as M.

[4]http://www.winson.com.tw/

[5]http://www.pjrc.com/teensy/

2. Clip the image by applying the threshold $T_{clip} = M - k$, where k is a small constant (Figure 3(b)).

3. If the largest connected shape hits the boundary, then shrink the image by increasing T_{clip} until it does not hit the boundary or until $T_{clip} = M$ (Figure 3(c)). This ensures the completeness of the shape to prevent reduced precision when the stylus is close to the boundary of the sensor board.

4. Compute the centroid of the shape as $O = (O_x, O_y)$. Then, the obtained O and M represent the position and the magnitude of the field, respectively.

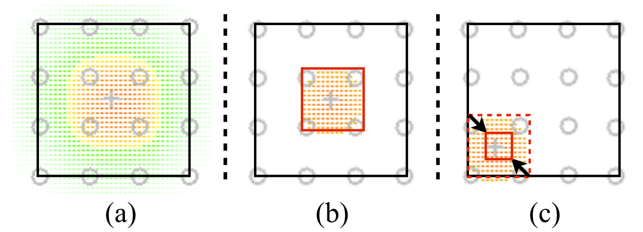


Figure 3. Image of magnetic field (a) without and (b) with clipping. (c) Shrink the image when close to the boundary.

Register a stylus: A user can register the stylus by placing it in contact with the surface without lifting it tip. Sixty consecutive M would be collected after the sensor readings become stable, and the threshold for determining the contacting event of a stylus, $T_{contact}$, can be obtained as $\bar{M} - 2\sigma$, where $\bar{M}$ and σ are the mean value and standard deviation of the collected values, respectively.

Sense through Surfaces

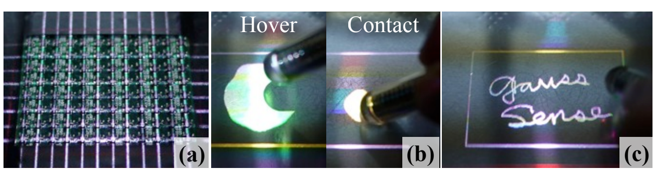


Figure 4. (a) Experimental apparatus. A top-mounted projector is used to provide visual feedback. (b) Image of magnetic field. (c) Results of stylus detection.

An example surface (Figure 2(b)) is made of a 3.5mm-thick wooden board that is coated with a 0.2mm-thick aluminum sheet, which represents the coating of common electronic devices, such as tablet computers. Since this surface is thick, opaque, solid, and made of conductive material, any conventional stylus detection system would fail if it was attached behind it. However, *GaussSense* can accurately detect the stylus through this surface as shown in Figure 4.

Use with Touchscreens

The sensor board also can be attached to the back of touchscreen devices as an extra sensor for stylus input. An unmodified iPod touch[6] was used for prototyping (Figure 5(a)). A sensor board is fixed to an acrylic protection case, which can

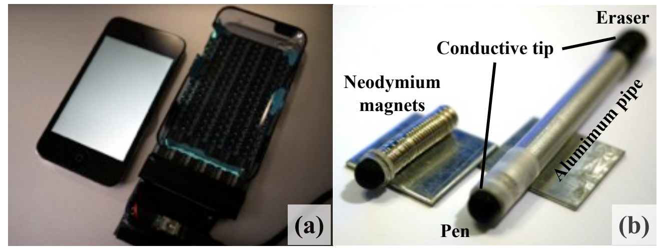


Figure 5. (a) Thin form-factor sensor grid augments magnetic field sensing on the multitouch device. (b) Magnetic stylus with one end as pen point and the other end as eraser.

be easily attached to or detached from the device. The magnetic stylus is also modified for the capacitive touchscreen by encasing in it stacked magnets in a conductive aluminum pipe with a rubber tip, which was taken from an Elecom iPhone stylus[7] (Figure 5(b)).

After the stylus has been registered on the touchscreen, the correspondence between touchscreen inputs and the magnetic sensor inputs is established. Therefore, the actual stylus touch point, $P = (P_x, P_y)$, along with O and M (Figure 6(a)), can be used to perform the following functions.

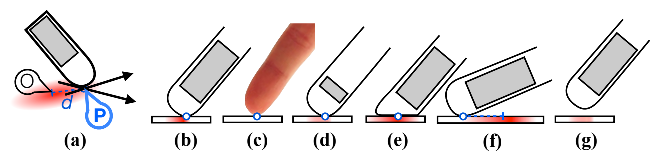


Figure 6. Sensing with touchscreens. Red: Magnetic field intensity. (a) Overview, (b) stylus event, (c) touch event, (d) different stylus, (e) various pressures, (f) different tilt angles, and (g) hover.

Distinguish the magnetic stylus from fingers: A magnetic stylus touch event can be distinguished from finger or conventional stylus touch events. If M exceeds a predened threshold, P will be regarded as a magnetic stylus event (Figure 6(b)) rather than a touch event (Figure 6(c)).

Recognize different styli: Different magnetic styli may yield different values of M when the tip comes into contact with the touchscreen. This fact can be exploited to distinguish among different styli (Figure 6(d)).

Pressure Sensing: When a user applies pressure through the tip, the rubber becomes deformed and the distance between the embedded magnets and the sensor board is shortened. Hence, the sensed value of M increases (Figure 6(e)).

Tilt Sensing: The relative position of O and P may change when the stylus is tilted. Therefore, $\vec{d} = \vec{PO}$ and $d = ||PO||$ can be applied to determine the direction and angle of tilt (Figure 6(f)), respectively.

Hover sensing: When the system senses a magnetic field, but no touching point P within a predefined distance r from the calculated centroid O, then the point O can be treated as the hover point (Figure 6(g)).

[6] http://www.apple.com/ipodtouch/

[7] http://www.elecom.co.jp/

APPLICATION AND PILOT STUDY

A simple sketching application is implemented to gather information concerning early user experiences. A user can draw a stroke in a natural manner, tilting the stylus (Figure 7(a)) and applying different pressures (Figure 7(b)). If the user wants to erase strokes, he/she can use the other end of the stylus as an eraser (Figure 7(c)), in which is embedded a 6mm-diameter $\times$ 1mm-height cylindrical magnet within another conductive rubber tip. The stroke is rendered by a mesh of triangular elements based on the position of the current $\overline{OP}$ and the previous $\overline{O'P'}$ pairs, and the intensity of the color inside the triangles is determined as the corresponding magnitude, M, as shown in Figure 7(d). A higher sensed M corresponds to the rendering of a darker stroke. A finger touch event on the top left-hand corner requests a new canvas. The boundaries of the sensor board can also be utilized for alternative input functions. Causing the stylus to hover at a boundary can call out an off-screen color swatch from which a new color can be selected.

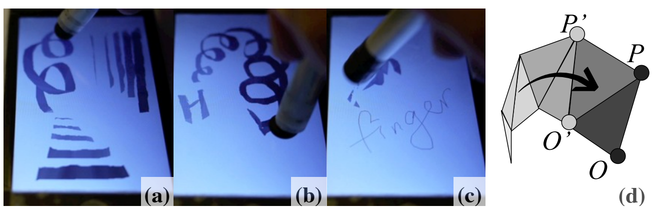


Figure 7. (a) Sensing of tilt angle. (b) Sensing of pressure. (c) Implicit mode switching for erasing. (d) Rendering of a pen stroke.

Pilot Study

Twelve volunteers (five female) were recruited through a designer's workshop as shown in Figure 8. Six of the 12 had more than five years of experience in product design. They were invited to try out all the features of the developed system and share their thoughts.

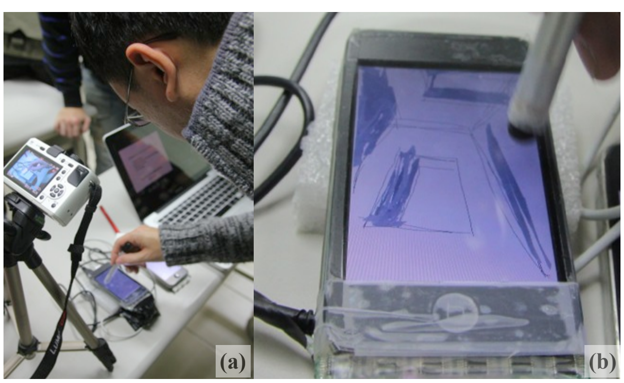


Figure 8. (a) Pilot study is conducted as part of a workshop. (b) A professional designer sketches using *GaussSense*.

All of the participants were surprised that a simple add-on technology could provide all of the aforementioned features. While sketching on the touchscreen, they found that they could use natural movements and they were felt satisfied with the precision. Two of them said that using the stylus reminded them of using a marker pen or a pen brush. Another designer thought that palm rejection should also be provided, because he preferred to place his hand on the screen while sketching. We also observed that several participants spontaneously used their fingers to blur the sketched lines, but this feature was not provided. Some of them suggested that the finger could be utilized to change the color or the simulated type of brush. One designer, who has many years of experience of using a digital pen for sketching, suggested that several well-established UI features, such as hover widgets [4], pressure widgets [10], and tilting menus or operations [15, 19] should be included in the application for advanced editing. Generally, the provided technology aroused the interest of the designers in trying the different combinations of features and discussing possible alternative designs.

EVALUATION

A series of formal measurements are made on the prototype devices to elucidate their various limitations. Measurements were made in two parts. In part I, the capabilities of the magnetic stylus on a *GaussSense*-enabled capacitive touchscreen, including precision, determination of applied pressure and determination of tilt angle, are measured. In part II, the penetrability of the magnetic field from the magnetic stylus through various materials of different thicknesses is measured. The prototype devices that were presented in the preceding section are used in the experiments.

Part I: Use of Magnetic Stylus on Capacitive Touchscreen

Experiment 1 - Precision of the Stylus: An acrylic case was used to hold the stylus perpendicular to the sensor board as Figure 9(a) shown. An arbitrary curve was drawn ten times, and the system registered a total of 13,684 pairs of (P_i, O_i), which is the touchscreen input and the calculated centroid of the magnetic field, respectively (Figure 9(b)). The Euclidian distance from each P_i to O_i is calculated, and the mean of the distances among the paired points is 0.42mm (SD = 0.27mm), which is the calculated precision of positioning.

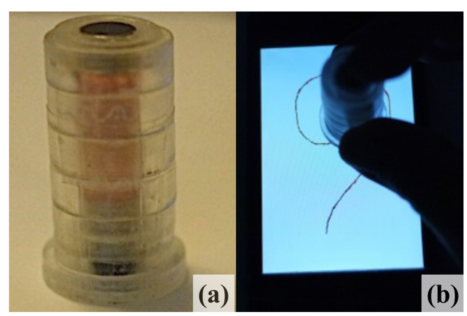
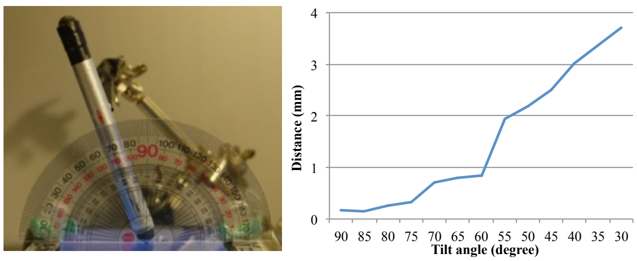


Figure 9. (a) Apparatus for testing. An acrylic case is used to keep a stylus perpendicular to the sensor board. (b) Drawing an arbitrary curve for sampling; the connected black and red points represent positions P and O, respectively.

Experiment 2 - Tilt Angle of the Stylus: A mechanical arm is used to fix the stylus and a protractor is placed beside to measure the included angle between the stylus tip and the screen as shown in Figure 10(a). The data are sampled every five degrees. At each tested angle, the system samples 100 times and the mean value of the detected angle is calculated. The result is shown in Figure 10(b) Owing to the roundness of the soft tip, the slopes of d in the range from 60 to 90 degrees differ from those in the range from 30 to 60 degrees. Because of physical limitations, the tips cannot be detected at angles from 0 to 30 degrees.

After the measurements were made, we conducted Experiment 1 again to obtain the standard deviations of position SD_p, which was measured to be 0.22mm. Set the range for each level to be 0.88mm, which is $\pm\, 2SD_p$, five angles of tilt were obtained.

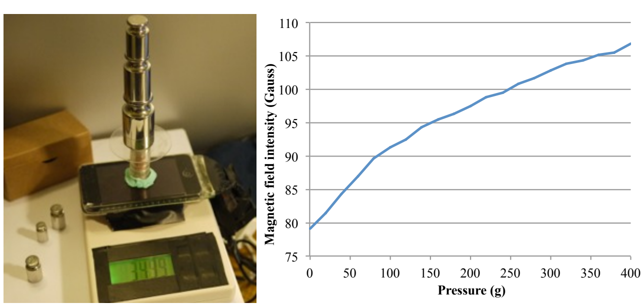


(a) (b)

Figure 10. (a) Experimental apparatus. (b) Sensed values. At 90 degrees on horizontal axis, stylus is perpendicular to sensor board.

Experiment 3 - Pressure of the Stylus: An electronic scale with a precision of 0.1gram (g) was used as shown in Figure 11(a). In testing, stainless steel weights were used because stainless steel causes no significant magnetic interference with the magnets in the stylus[8]. An acrylic case was used to hold the soft-tipped stylus perpendicular to the screen. In each trial, a 20g weight was put on the stylus. The total weight never exceeded 400g, and each total weight was used in 100 trials. The mean value was calculated, as shown in Figure 11(b).

After the measurements were made, standard deviations of the magnitude of magnetic field, SD_m, were determined using the same procedures as were used in Experiment 1. The magnitude fluctuated slightly (SD_m=1.15 Gauss) while the stylus was moved around. Set the range for each level to be 4.6 Gauss, which is $\pm\, 2SD_m$, six pressure were obtained.



(a) (b)

Figure 11. (a) Experimental apparatus. (b) Results of magnetic field intensity using 0 to 400g weights.

[8]Conventional stainless steel is not entirely non-magnetic, but its relative permeability (<1.1; 1 is for non-magnetic) is much smaller than those of most ferromagnetic materials (between 100 and 20000). Given the precision of our developed device, the interference associated with the use of stainless steel is negligible.

Part II: Magnetic Stylus on Arbitrary Surface

Experiment 4 - Surface material: Since a magnetic field can pass through most physical materials, input capability can be enabled on the surface. An initial exploration of this property was conducted by attaching the sensor board behind different materials that were a) opaque, b) conductive or c) ferromagnetic, as shown in Figure 12.

The experimental results reveal that a magnetic field can pass through all of the materials except for the ferromagnetic material. Ferromagnetic materials not only interfere with detection, but also inhibit drawing because of the strong attraction between the magnetic stylus and the ferromagnetic surface.

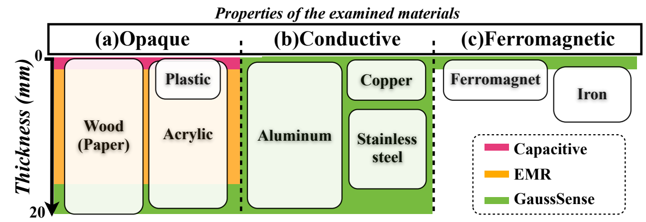
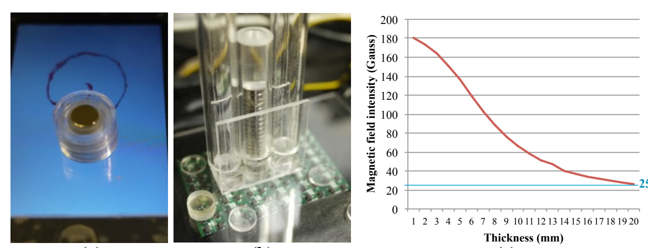


Figure 12. All technologies are effective when opaque materials are thin, but only *GaussSense* works also on conductive and ferromagnetic materials. Except on ferromagnetic materials, *GaussSense* works well with material thicknesses of under 20mm. Generally, *GaussSense* has larger sensing range than capacitive or EMR technology.

Experiment 5 - Thickness of the non-ferromagnetic surface: According to Experiment 4, the sensing ability of on a non-ferromagnetic surface is limited by its thickness. To understand this fact, Experiment 1 was firstly conducted with small magnets to find the minimal magnetic field strength that could be stably detected through the device, iPod Touch, by the sensor board at a distance between the magnet and the sensor board of 8.8mm as shown in Figure 13(a). The input data of the capacitive touchscreen are used as ground truth. After 50 trials, 25 Gauss was found to be the minimal field strength that yielded a mean error of under 1mm.



(a) (b) (c)

Figure 13. (a) Small magnet is used to find the minimal magnetic field strength, which is determined to be 25 Gauss. (b) Magnetic stylus in a vertical sliding case. Acrylic chips are used to control distance between sensor and stylus. (c) Sensed field strength decreases as distance between stylus and sensor increases.

Thereafter, the magnetic stylus was tested on the sensor board (Figure 13(b)) in the absence of any electronic components within the device, which may otherwise have interfered with the experiment. An acrylic sliding case was used to hold the stylus perpendicular to the sensor board. In each trial, one more 1mm acrylic chip was added between the magnetic pole and the sensor board; 100 measurements of magnitude were made at five fixed sample points, and the mean value was calculated as shown in Figure 13(c). The results show that the developed technology can be used with this device with a thickness of under 20mm. Though iPod Touch is used as the examined material, the results also can be applied to any uniform non-ferromagnetic materials, because the magnetic field penetrates them easier.

DISCUSSION

Limitations

To ensure uniform precision, the sensor board must be kept parallel to the interactive surface on the front of the device. Accordingly, the case that holds the sensor board should not be made of a soft material, such as silicon, to prevent the user from accidentally displacing the calibrated sensor while holding the device.

Since the system exploits magnetism, the *GaussSense* system cannot be combined with some sensors that also use magnetism, such as a magnetometer, and cannot be used with ferromagnetic materials.

A stylus that contains a strong magnet may erase content on magnetic strips on credit cards if they are very close to each other, because magnetic strips are not protected by shielding mechanism. However, the magnet does not affect IC cards, flash storage devices, or well-shielded magnetic storage devices. Crafting a stylus with magnetic shielding materials can mitigate this potential hazard.

Fault Tolerance

In deploying numerous sensors on the board, generally, two problems may be encountered. First, the sensors have different sensitivities, and second, some may be defective. With respect to the first problem, the initially sensed values can be adjusted by the aforementioned calibration process, and with respect to the second, a fault tolerance procedure is developed to recover the values of defective sensors.

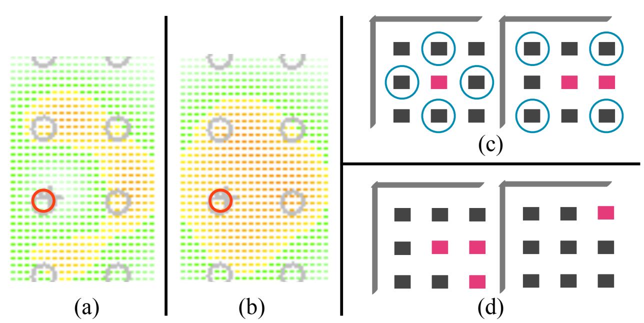


Figure 14. Fault tolerance. (a) Without and (b) with recovery of value that cannot be measured by invalid sensor, which is indicated by red circle. (c) Recoverable cases and (d) unrecoverable cases. Red: Invalid sensor(s). Blue circle: Candidates for recovering.

When the sensors are activated for the first time, a self-validation test records the first n values that are sampled from each sensor i, and the mean $\bar{v}_i$ and standard deviation σ_i are calculated. If the calculated values satisfy the following two conditions, then the sensor will be recognized as operating correctly. First, the $\bar{v}_i$ must lie in a predefined range. Second, the σ_i should not be larger than a predefined threshold. Any sensor that cannot meet these criteria will be regarded as invalid. To recover the measurements would have been made by the invalid sensors, bi-linear interpolation using the values measured by the neighboring sensors can be applied as shown in Figure 14(a). However, if the invalid sensor is at the boundary or no valid neighboring sensor (Figure 14(b)) can be used for interpolation, the values in question cannot be recovered.

Compatibility with Various Surfaces

Integration with a resistive touchscreen: GaussSense is also compatible with resistive touch panels. A well-calibrated 3.8" resistive touchscreen is laid over the screen of an iPod Touch, which is only used for displaying as shown in Figure 15. Because a steady pressure must be applied to the touchscreen, the stylus tip is made of a magnetic cone with 1mm-diameter tip. *GaussSense* not only detects the hover status of the stylus, but also reduces the required initial force that must be applied to the resistive touchscreen. To enable pressure sensing, *GaussSense* can be further integrated with a pressure-sensitive IFSR [13] touch panel.

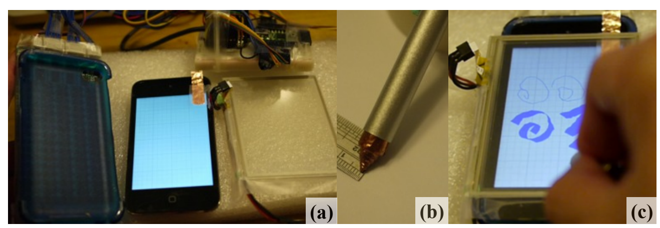


Figure 15. (a) From left to right: modified plastic case, unmodified iPod touch, and well-calibrated resistive touchscreen. (b) Stylus with magnetic cone. (c) Results of stylus detection.

Integration with a LCD Screen: The sensor board can be attached to the back of a laptop monitor as shown in Figure 16. A user can use the registered stylus to write directly on the unmodified LCD monitor. He or she can, for example, sign a personal signature, scribble ideas to be communicated with others, or leave memos.

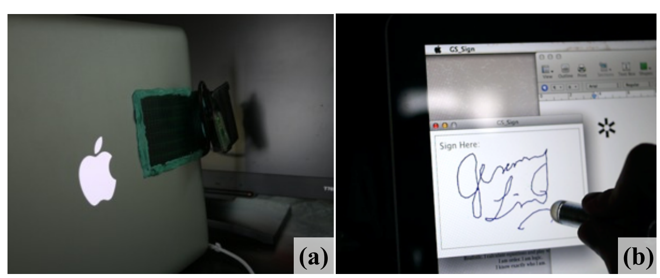


Figure 16. (a) Attaching sensor board to back of laptop monitor, and (b) taking a note.

CONCLUSION AND FUTURE WORK

This paper presents a novel back-of-device sensing method, *GaussSense*, to enable a stylus to be used as an input device on any non-ferromagnetic flat surface that is thinner than 2cm by utilizing directional magnetism. Since most handheld touch devices are thinner than 2cm, the *GaussSense* board can be attached to the back of these devices as an additional sensor to improve their capabilities of stylus input. The board enables touch events that are caused by fingers to be distinguished from those that are caused by the stylus; it also enables the tilt angle of the stylus, the applied pressure, and the position over which the stylus hovers to be detected. Through a series of evaluation, the functions of the developed technology are examined, and the results can be further improved by better manufacturing processes. Since *GaussSense* can discriminate touch points using a finger from those using a stylus, future work should seek to develop richer Pen+Touch interactions. An advanced user study can also be conducted to understand usability issues.

The proposed *GaussSense* technology enables or enhances stylus input without modifying the front surface. The solution is cheap and robust, and the calculations involved are sufficiently simple to be performed in real time.

ACKNOWLEDGEMENTS

We gratefully acknowledge the helpful comments and suggestions of the Associate Chairs and the anonymous reviewers. We also thank Ming Ouhyoung and Mike Y. Chen for their valuable comments. This paper was partially supported by the Excellent Research Projects of the National Taiwan University under NTU10R80919-5, National Science Council of Taiwan under NSC100-2221-E-001-006-MY2, and the MediaTek Fellowship.

REFERENCES

1. Ashbrook, D., Baudisch, P., and White, S. Nenya: subtle and eyes-free mobile input with a magnetically-tracked finger ring. In *Proceedings of ACM CHI 2011* (2011), 2043–2046.
2. Bi, X., Moscovich, T., Ramos, G., Balakrishnan, R., and Hinckley, K. An exploration of pen rolling for pen-based interaction. In *Proceedings of ACM UIST 2008* (2008), 191–200.
3. Dietz, P., and Leigh, D. DiamondTouch: a multi-user touch technology. In *Proceedings of ACM UIST 2001* (2001), 219–226.
4. Grossman, T., Hinckley, K., Baudisch, P., Agrawala, M., and Balakrishnan, R. Hover widgets: using the tracking state to extend the capabilities of pen-operated devices. In *Proceedings of ACM CHI 2006* (2006), 861–870.
5. Harrison, C., Benko, H., and Wilson, A. D. OmniTouch: wearable multitouch interaction everywhere. In *Proceedings of ACM UIST 2011* (2011), 441–450.
6. Harrison, C., and Hudson, S. E. Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices. In *Proceedings of ACM UIST 2009* (2009), 121–124.
7. Hinckley, K., Yatani, K., Pahud, M., Coddington, N., Rodenhouse, J., Wilson, A., Benko, H., and Buxton, B. Pen + touch = new tools. In *Proceedings of ACM UIST 2010* (2010), 27–36.
8. Hook, J., Taylor, S., Butler, A., Villar, N., and Izadi, S. A reconfigurable ferromagnetic input device. In *Proceedings of ACM UIST 2009* (2009), 51–54.
9. Perski, H., and Morag, M. Dual function input device and method. U.S. Patent No. 6762752, 2002.
10. Ramos, G., Boulos, M., and Balakrishnan, R. Pressure widgets. In *Proceedings of ACM CHI 2004* (2004), 487–494.
11. Rogers, S., Williamson, J., Stewart, C., and Murray-Smith, R. FingerCloud: uncertainty and autonomy handover incapacitive sensing. In *Proceedings of ACM CHI 2010* (2010), 577–580.
12. Rogers, S., Williamson, J., Stewart, C., and Murray-Smith, R. AnglePose: robust, precise capacitive touch tracking via 3d orientation estimation. In *Proceedings of ACM CHI 2011* (2011), 2575–2584.
13. Rosenberg, I., and Perlin, K. The UnMousePad: an interpolating multi-touch force-sensing input pad. *ACM TOG 28*, 3 (2009), 65:1–65:9.
14. Steurer, P., and Srivastava, M. B. System design of smart table. In *Proceedings of IEEE PerCom 2003* (2003), 473–482.
15. Tian, F., Xu, L., Wang, H., Zhang, X., Liu, Y., Setlur, V., and Dai, G. Tilt menu: using the 3D orientation information of pen devices to extend the selection capability of pen-based user interfaces. In *Proceedings of ACM CHI 2008* (2008), 1371–1380.
16. Vogel, D., and Casiez, G. Conté: multimodal input inspired by an artist's crayon. In *Proceedings of ACM UIST 2011* (2011), 357–366.
17. Vokoun, D., Beleggia, M., Heller, L., and Šittner, P. Magnetostatic interactions and forces between cylindrical permanent magnets. *J. Magnetism and Magnetic Materials 321*, 22 (2009), 3758–3763.
18. Wilson, A. D., Izadi, S., Hilliges, O., Garcia-Mendoza, A., and Kirk, D. Bringing physics to the surface. In *Proceedings of ACM UIST 2008* (2008), 67–76.
19. Xin, Y., Bi, X., and Ren, X. Acquiring and pointing: an empirical study of pen-tilt-based interaction. In *Proceedings of ACM CHI 2011* (2011), 849–858.