Using Electromagnetic Input for Multi-User or Two-Handed Spatial Gestural Interaction based on the Digital Compass

Kamer Ali Yuksel
Sabanci University
Computer Vision and Pattern Recognition Laboratory
kamer@sabanciuniv.edu

Ipek Baz
Sabanci University
Computer Vision and Pattern Recognition Laboratory
ibaz@sabanciuniv.edu

Haluk Ozduman
Technical University of Berlin
German Turkish Advanced Research Center for ICT
haluk.ozduman@gt-arc.com

ABSTRACT
Multiple researchers recently proposed the use of the digital compass embedded in mobile devices for touchless interaction in the 3D space around them. These methods overcome several limits imposed by other interaction techniques and were evaluated for a variety of uses. However, they do not support collaborative settings and are prone to dynamic noise caused by external conditions, as with most other sensor-based interaction techniques. In this paper, we propose the use of frequency-modulated electromagnets as an input medium for magnetic interaction to overcome its various constraints and further enable multi-user and two-handed input. Furthermore, we demonstrated the hardware design specifications of a novel input device, referred to as electromagnetic stylus, which is prototyped to conduct a user-study on the proposed method. Experimental results indicate that gestures performed simultaneously by four electromagnetic styli can accurately be recognized using a single magnetic field sensor, and dynamic noises can be substantially reduced.

Author Keywords
Around device interaction; magnetic field sensor; mobile devices; solenoid driver circuit; electromagnetic stylus.

ACM Classification Keywords
H5.2 Information interfaces and presentation: User Interfaces, Input devices and strategies.

INTRODUCTION
Mobile phones are capable of accomplishing a broad range of activities and have started to replace personal computers. However, human factors, such as finger size, often prevent interactions required for collaborative applications and applications that involve complex data. This is mostly due to the limited size of mobile devices [17]. Today's display technology is capable of moving the images out of the screen and into the space immediately surrounding the device. Researchers attempted to develop novel methods and technologies for around-device interaction (ADI) in order to extend the interaction space of mobile devices beyond their physical boundaries [3, 9, 20]. However, most of these sensor-based interaction techniques do not allow simultaneous inputs.

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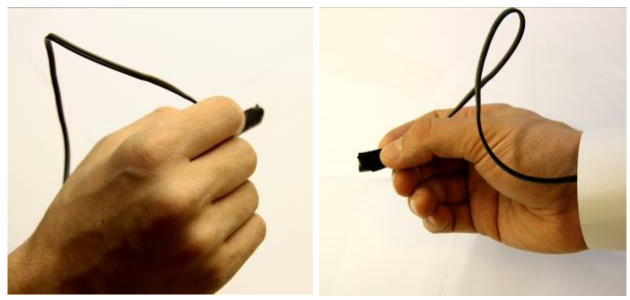

Figure 1. Electromagnetic-stylus for multi-user or two-handed 3D spatial interaction around mobile devices.

Several researchers recently proposed the use of embedded digital compass (magnetometer) for touchless interaction in the 3D space around mobile devices [1, 8, 11]. This method allowed ADI by sensing the position, orientation, velocity, and acceleration of a passive magnetic token. Throughout this paper, we refer to all of the interaction methods that utilize an untethered permanent magnet for making coarse gestures around mobile devices as Magitact. Magitact overcomes several limits imposed by other ADI methods. However, it does not support bimanual or collaborative settings and is prone to dynamic noise within the magnetic field caused by external conditions.

In this paper, we propose the use of electromagnets instead of permanent magnets to overcome the limitations of Magitact. Furthermore, we introduce the electromagnetic sylus, a novel input device (Fig. 1) that is capable of modulating its magnetic strength with given frequencies. Moreover, we conduct a user study on the accuracy and noise-resistance of the proposed method in recognizing around-device gestures. The results indicate that the proposed method is significantly more noise-resilient than the previous work, employing permanent magnets and is able to recognize gestures performed simultaneously by three electromagnetic styli using a magnetometer embedded in present mobile devices with an accuracy above 80%.

BACKGROUND AND MOTIVATION

Magitact overcomes several limitations imposed by other interaction techniques and has been evaluated in a variety of uses [11, 12, 13, 23]. For instance, in the case of accelerometer-based input, users must rotate the entire mobile device to indicate the rotation of a virtual object, while it is easier to rotate something held by the fingers rather than rotating the hand due to kinematic constraints [15]. Instead, Magitact uses the global coordinate frame of the device as a recalibration mechanism for mapping the absolute position to a new logical position, allowing the user to specify a comfortable resting position in the real world as a center point for the interaction space [10].

However, Magitact does not support collaborative settings, multiple concurrent inputs or the use of both hands, as the digital compass recognizes the strength and orientation of the cumulative magnetic field around the device and is not able to separate multiple permanent magnets. Furthermore, it is prone to dynamic noise caused by external conditions, as most other sensor-based interaction techniques. In contrast, the use of electromagnets not only extends the application space of Magitact by allowing simultaneous around-device inputs, but also provides a reliable mode switch for enabling/disabling the magnetic source. Hence, it allows for a clutching action that a relative pointing scheme requires, as only intentional gesturing is processed by the system [4].

Multiple concurrent inputs are often desirable as they improve the efficiency of human-computer interaction by enabling users to perform two sub-tasks in parallel, rather than as sequentially selected modes [5]. According to Hinckley et al. [10], people are good at experimenting with 3D spatial relationships between real-world objects, but they possess little innate comprehension of abstract 3D space. Hence, it is often difficult for users to correlate the position of the pointer in space with the position of the tool on the screen [6]. Thus, users require less concentration to manipulate objects relative to one another than if one object was fixed in space and a single input sensor controlled the other [20]. Their perceptual system needs a spatial reference, which may be a real-world object relative to which the user can gesture when interacting in 3D [10].

Enabling the use of both hands allows users to ground themselves in the interaction space, in essence, because their own body becomes a spatial reference [10]. The simultaneous use of two input devices takes advantage of people's innate ability of knowing precisely where their hands are relative to each other [20]. Thus, the use of two hands can also help make the spatial input comprehensible to users when interacting in 3D [10]. For that reason, users can transfer everyday skills for manipulating tools with two hands to the operation of a computer with little or no training [5].

For the desktop environment, there are several 3D input-devices, which provide six degrees of freedom (6-DOF) based on the electromagnetic sensing technology for virtual scene navigation and object manipulation in 3D immersive virtual environments and display platforms. In contrast with the proposed method, these devices utilize a central magnetic resource to provide fast and accurate spatial data via multiple magnetic trackers. The proposed method does not provide real-time spatial interaction and is limited to gestural interaction. However, it is much cheaper and compatible with mobile environments, as it does not require any big infrastructure or change in the specifications of the existing mobile devices with an embedded digital-compass.

To the best of our knowledge, there is no other work that employs electromagnets for multi-user or two-handed gestural interaction around mobile devices. Lian et. al. [16] enabled multi-token interactions on portable displays by eliminating the interference between magnetic tangibles via galvanized steel cases. Recently, Bianchi et. al. [2] explored the use of multiple tokens with varying magnetic flux to develop a magnetic tracking system. Instead of using electromagnets, they used a motor to spin a permanent magnet to create a sinusoidal temporal pattern of unique frequency for each token. In contrast with our work, their method does not allow coarse gestures because it is limited to only six pre-calibrated locations for tangible ADI.

METHODOLOGY

The proposed method allows one or more users to interact with a mobile device by manipulating the magnetic field using one or multiple magnetized styli (Fig. 1). The magnetized styluses consist of a set of electromagnets, which are capable of modulating their current with different frequencies. Modulation of electromagnets with specific frequencies allows simultaneous use of these input devices in the vicinity of a single magnetometer. Demodulation of the cumulative signal enables tracking multiple magnetic tokens for bimanual interaction or multi-user input. Magitact is forwards compatible with the proposed method as a permanent magnet can be used w/o electromagnetic styli concerning the battery consumption or when a single token is sufficient. However, in that case, the dynamic noise within the vicinity of the device would primarily affect the performance of the permanent magnet. The electromagnetic stylus can also be set to constant current for backwards compatibility with Magitact.

Amplitude Modulation

In Magitact, the contribution coefficient of each permanent magnet to the axes of the sensed magnetic field depends only on the relative position (the distance) and the strength of the magnet, whereas modulating electromagnets with different frequencies results in another parameter for the contribution coefficient. This parameter can be used to calculate the instantaneous strength of each electromagnet to separate their individual effects due to their instantaneous position at a given time. These positions can be collected to find trajectories of each stylus used by one or more users while performing gestures.

In the presence of multiple effectors, the magnetometer measures the sum of the magnetic field strength applied by each permanent magnet and electromagnet, in addition to the static and dynamic magnetic noise present within the environment. In order to modulate the magnetic moment of each electromagnet as sinusoids with different frequencies, we have designed a solenoid driver circuit that alters the current flowing through each of them (by applying a sharp band-pass filter). Demodulating the signal containing the aggregation of those magnetic sources can calculate the contributions of each electromagnet to the magnetic field sensed by a single magnetometer. Since specific frequencies are focused while demodulating, reasonable static and dynamic noises – encountered through the daily routine of a regular user – can be filtered out.

However, the magnetic moment of a permanent magnet is constant and does not require an external power supply, as opposed to the case of electromagnets. Also, the magnetic force of electromagnets should be compatible with permanent magnets of the same size, using low currents (e.g. 0.1-0.2 Amperes) to provide the same quality of interaction with low power-consumption. Hence, the user can simply use a permanent magnet to prevent the power consumption in the case of a single-user or one-handed interaction. Furthermore, multiple magnetic sources may also include a single permanent magnet, which can be distinguished (after the effects of electromagnets are subtracted) if the dynamic noise within the environment can be neglected. Similarly, the electromagnet can also be used as a permanent magnet by employing a constant current rather than a sinusoidal one.

In the time domain, electromagnets that are set in different frequencies produce a mixed signal that can be separated in the frequency domain using various demodulation techniques. If the input and carrier signals are considered as pure sine waves with frequencies m and c, respectively, the frequency of the resulting signal would be (ω_m+ω_c) and (ω_m-ω_c) when the input signal is modulated with the carrier signal. The bandwidth can be filled with several different signals by modulating the input signal at different frequencies.

However, there are some issues that limits the maximum number of electromagnets and their modulation frequencies. The minimum interval between the frequencies of two consecutive modulated signals should not be too close in order for them to be separable during the demodulation phase. Furthermore, the maximum allowed sampling frequency of the magnetometer embedded in iPhone 5 limits the maximum frequency of each signal (to approx. ±300 Hz), and the interval between them, as it would be harder to separate signals by demodulation due to possible loss of data. Moreover, the frequency of each signal should be above the threshold to carry the characteristics of the user's hand-gestures, of which we have observed a maximum frequency of ±50 Hz. Finally, band-pass filters, which are utilized for demodulation, should not have too many taps for preventing delays and tolerance in limited bandwidth.

According to the Nyquist Sampling Theorem [18, 22], the signal can be perfectly reconstructed from an infinite sequence of samples if the sampling rate exceeds twice the highest frequency in the original signal. If the conditions of the theorem are not satisfied, distortion will occur, and some higher frequency components of the signal can be calculated as lower frequency components. In order to avoid any possible aliasing, the sampling frequency of the modulated signals should be at least ±100 Hz to sufficiently capture each peak throughout the signal. However, one may prefer to use smaller frequencies in order to utilize the maximum possible number of simultaneously used electromagnets, due to the limitations of the frequency bandwidth imposed by the sampling frequency of the magnetometers embedded in present mobile devices.

Demodulation

The effect of a permanent magnet or constant current electromagnet (CCE) sensed by the magnetometer is directly relative to the 3D trajectory of the intended gesture (Fig. 2a). In contrast, the resulting signal is in the frequency-modulated form of the original trajectory (Fig. 2b), in the case of a sinusoidal current electromagnet (SCE). Hence, the envelope should be detected to recover the original information-bearing trajectory of the intended gesture separately in each axis. In order to recover original signal from the modulated carrier wave, a product detector is employed by multiplying the modulated signal with a pure sine signal with the same frequency of each carrier wave. This multiplication produces the input signal and another AM signal at twice the original carrier frequency. Therefore, applying a low-pass filter to the result of each multiplication leaves each original signal introduced by each electromagnet.

Double-sideband suppressed-carrier transmission (DSB-SC) is preferred for demodulation of double sided AM signals (Fig. 3b), as it is able to detect the envelopes of the signals in real-time and is immune from a carrier fade while rejecting unwanted signal sidebands (noise) [22]. Also, it does not require the sideband of the signal to be a perfect mirror image and can capture the signal with a minimum carrier, whereas other envelope detectors need 6.02 dB of carrier above the sideband signal. In this technique, frequencies produced by amplitude modulation are symmetrically spaced around the carrier frequency and the carrier level is almost completely suppressed. Furthermore, most of the dedicated power is distributed between the sidebands, as the carrier wave is not transmitted, which implies an increase of the cover in DSB-SC in comparison with other techniques. In order to detect the finite signals that are created after the demodulation phase in the low frequency range (Fig. 3c), we implemented a finite impulse response (FIR) low-pass filter for real-time usage. This filter reduces the delay by eliminating noise while it provides equal delay for all frequencies and does not require feedback.

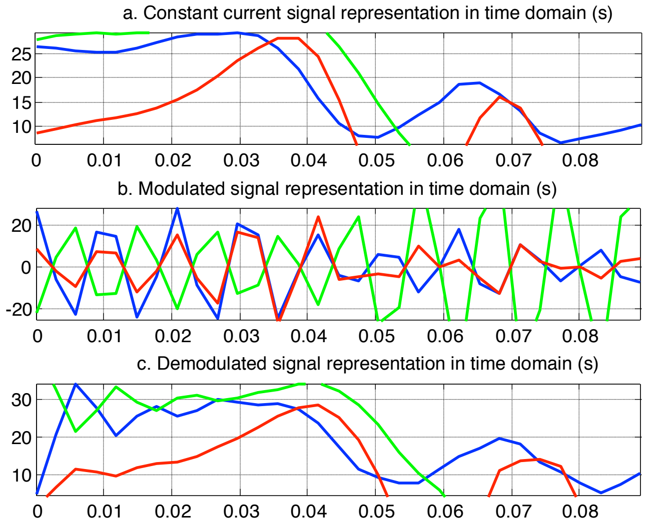

Figure 2. Time domain representations of the same 3D signal at various phases: (a) original, (b) modulated, (c) demodulated.

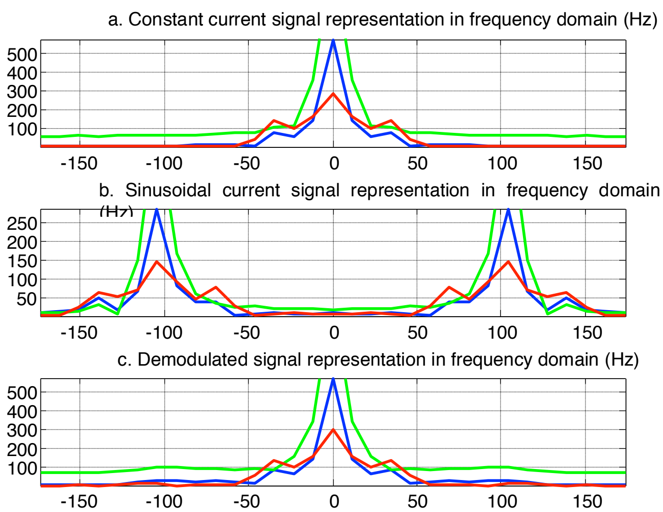

Figure 3. Frequency domain representations of the same 3D signal respectively at various phases: (a) original, (b) modulated, (c) demodulated.

The recorded mixture signal of around-device gestures of three digits (3, 2, and 6) simultaneously drawn using one CCE and two SCEs (100 and 150 Hz) is shown in the top of in a frequency domain representation. Firstly, DSB-SC is sequentially applied to detect envelopes for other digits recorded with the SCE (2 and 6) and eliminated them from the mixture (Fig. 4). Then, the digit recorded with the CCE (3) is reconstructed using the FIR low-pass filter. The performance of the demodulation can be observed visually as represented in Fig. 5 below. The figure includes the 2D representation of detected envelopes for each demodulated digit against their original signal recorded separately using CCE. Clearly, the overall characteristic of each gesture's trajectory is almost completely recovered, except for some distortion at the beginning of each gesture, which has a minor effect on the extracted features.

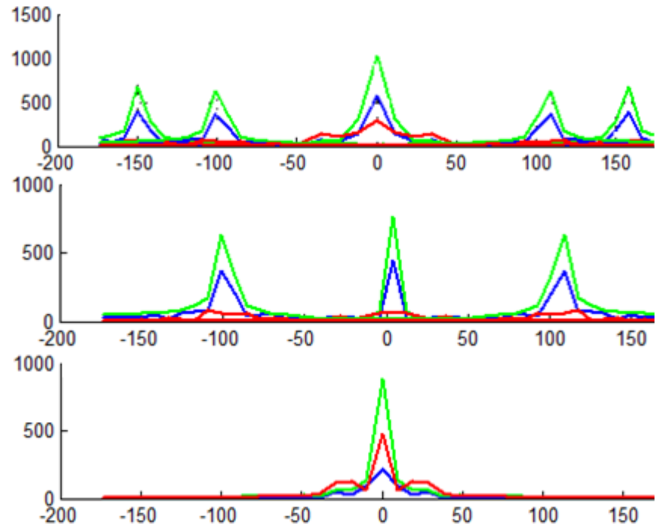

Figure 4. Frequency domain (Hz) representations after the sequential demodulation phases of three digits.

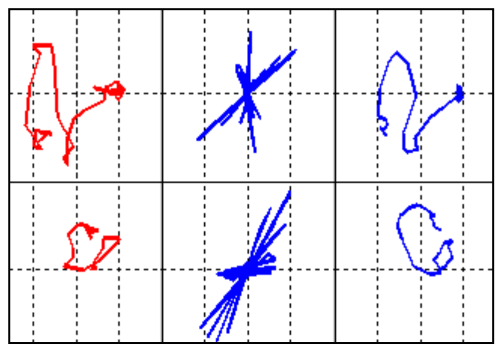

Figure 5. 2D representations of different gestures at various phases: original (right), modulated (middle), recovered (left).

EXPERIMENTS

In order to compare the proposed method with Magitact, we have conducted two experiments focusing on the accuracy of gesture recognition. Instead of using a permanent magnet, we have utilized a CCE for consistence with SCE in terms of the features of the magnetized token, in order to make a fair comparison of both methods. The first experiment aimed to investigate how the accuracy changes as the number of simultaneous tokens increase. The second experiment aimed to check how the accuracy changes as the background noise increases. In both experiments, we have used sample gestures of digits due to the average complexity of their trajectories. The frequencies of the digits, which were recorded with the CCE, varied between 10 and 50 Hz. To collect data, we have invited 10 users, divided them into two groups of five and assigned a digit to each of user for the sake of simplicity. Each group utilized the magnometer embedded in iPhone 5 for recording assigned gestures. The data collection was composed of five rounds. The first round initialized with a single CCE and a SCE is added in subsequent rounds. The frequencies of four SCEs were set to 100 Hz, 150 Hz, 200 Hz and 250 Hz; and the band-pass interval was set to 50 Hz to the maximum frequency of digits.

Recordings of the first round reflects the use of permanent magnet by a single-user as in Magitact and consists of 20 samples of each digit to be utilized as the training set. Recordings of subsequent rounds by both group are unified to compose four individual validation-sets with relation to the label of their rounds. In those rounds, 10 recordings from all possible combinations of digits were collected regarding the number of SCE simultaneously employed. Samples of digits are recovered from recordings in each validation-set using the demodulation procedure of the proposed method. To sum up, there were a total of 280 samples extracted from the recordings of validation-sets. For each sample, a feature vector of length 36 was extracted with the concatenation of the following 18 features for two time windows of equal size.

1. Mean, variance and standard deviation of the magnetic field change along *x, y* and *z*-axes and their Euclidian norm (12 features).
2. Piecewise correlation between the magnetic field strength along the three axes (3 features).
3. Spectral energy density of the magnetic field strength along *x, y*, and *z*-axes (3 features).

The features extracted from the training and validation sets were utilized for classification of gestures using a Multi-layer Perceptron (MLP). The leave-one-out cross-validation accuracy of the training set (94%) and the accuracy of each validation-set, which are labeled according to number of additional SCEs utilized, are shown in Fig. 6. To sum up, the classification accuracy is inversely proportional to the number of electromagnets that was concurrently employed. Furthermore, results indicate that a magnetometer with a sampling frequency of ±300 Hz would allow concurrent utilization of up to three electromagnets (1 CCE + 2 SCE), with an accuracy above 80%. Moreover, the system would recognize gestures, which can be performed by two people using both of their hands, with a fair accuracy of 67%.

For the second experiment, we compiled other validation sets by adding different levels of white Gaussian noise to 20 samples of each digit, which were collected independently by both CCE and SCE. The gesture recognition accuracies of both types of electromagnets resulted in different signal-to-noise ratio (SNR) levels and are shown in Fig. 7. The results of the second experiment indicated that permanent magnets could only be utilized up to an SNR of 30 dB, as their accuracy drops dramatically afterwards. In contrast, SCEs are much more resilient to noise, as they allow for the recovery of the original signal (Fig. 8). In fact, at an SNR of 20 dB, they have an equivalent performance to a permanent magnet at an SNR of 30 dB, and their accuracy drops much more smoothly in lower SNR levels.

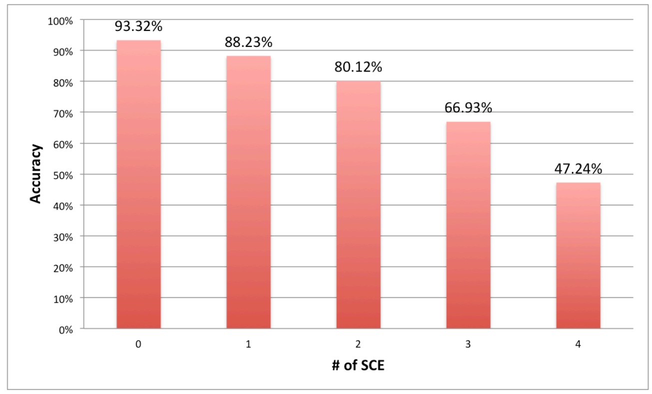

Figure 6. Gesture recognition accuracy according to the number of SCEs utilized simultaneously with a CCE.

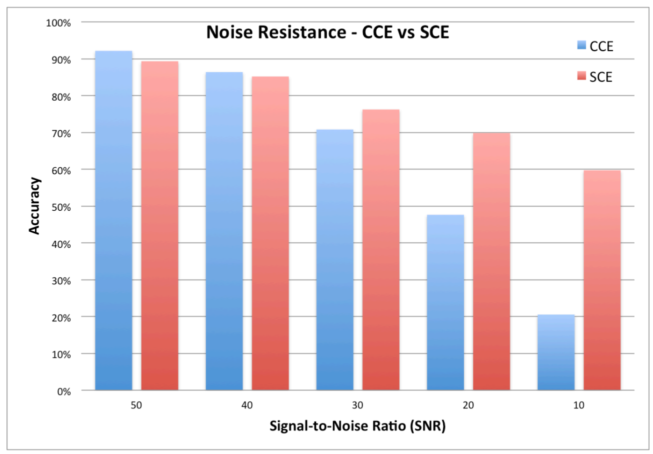

Figure 7. Gesture recognition accuracy resulted in different signal-to-noise levels while using CCE or SCE.

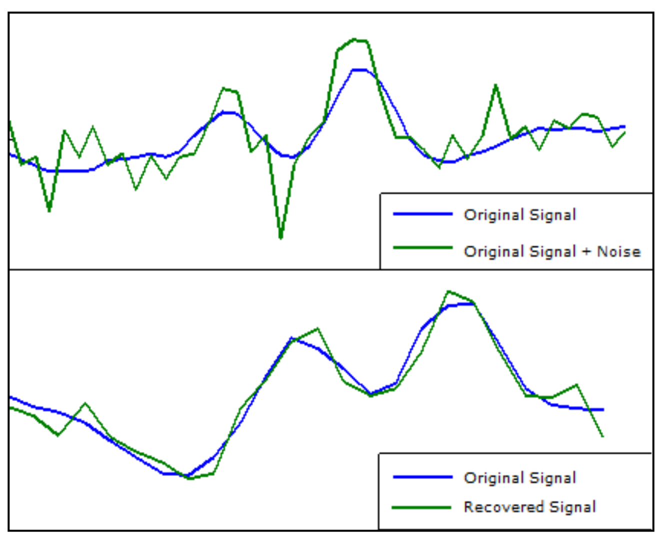

Figure 8. Time domain representations of original and reconstructed signal w/o white Gaussian noise.

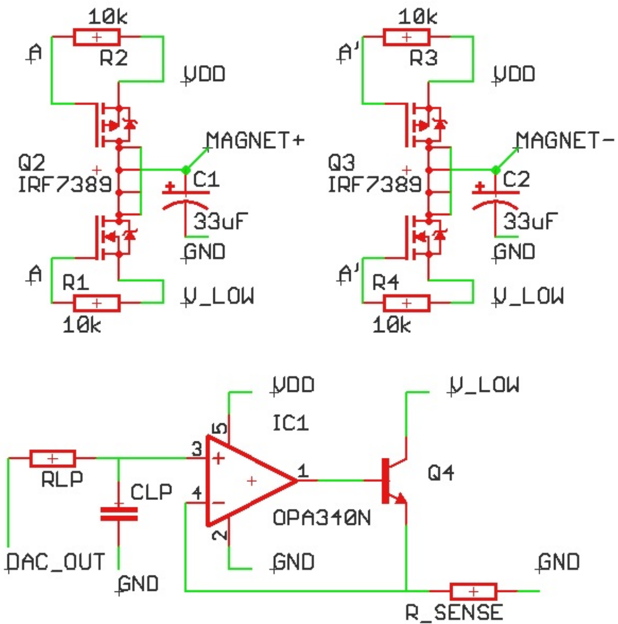

Figure 9. Schematic of the solenoid driver circuit.

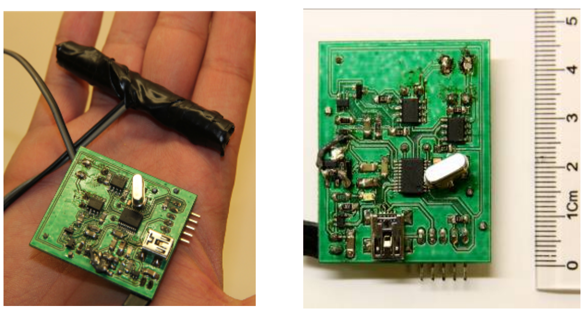

Figure 10. The PCB of the solenoid driver circuit.

HARDWARE DESIGN

In order to implement an electromagnet that is capable of modulating its magnetic strength with a given frequency and amplitude, we designed a solenoid driver circuit (Fig. 9). The solenoid driver circuit is able to alter the current passing through the electromagnet in constant and sinusoidal modes. Adjusting the amplitude of the sinusoidal current can alter the maximum operational distance. Ferrite (manganese-zinc) core is utilized for electromagnets due to modulation, as it looses its magnetic strength instantly after being disconnected from the power supply, as opposed to steel core that also produces 50 times weaker magnetic strength. To produce a magnetic strength equivalent to that of permanent magnets, a high current source was required for the prototype. However, we did not choose to use high output batteries to provide such a current, due to the size constraints of the prototype. To supply the high current source, we decided to drive the circuit using an (rail-to-rail input/output) operational amplifier (op-amp) to maximize the signal range. To apply a current across a load in either direction (to change the current bi-directionally), we also implemented a low-power switching system using two Power MOSFETs (Fig. 9, Q2 & Q3), controlled by two output pins of the microcontroller. MOSFET pairs with a very low internal resistance (0.029 Ω & 0.058 Ω) were chosen due to their low power consumption, voltage drop and large headroom. Also, the switching system fits into a small area since it only includes two discrete components. Finally, we used two polarized capacitors (Fig. 9, C1 & C2), which are connected both ends of the electromagnet to the ground, in order to overcome ringing problems while driving an inductive load.

Measurements

The Printed Circuit Board **(**PCB) of the solenoid driver circuit is approximately 20 g in weight and 4 x 4.5 x 0.5 cm in size (Fig. 10) when printed using the single-layer implementation technique, but it can be further reduced using multi-layer implementation. To experiment this, we coiled two electromagnets of the same length (6 cm) with different diameters (1.5 or 1 cm), using ferrite as the core material. The cable was coiled approximately 450 and 200 times for the larger and smaller-diameter electromagnet. The maximum operational distances of both electromagnets are around 20 cm for reliable interactions. The resulting electromagnets had an inductance / resistance of 14 mH / 12.8 Ω and 2 mH / 5.6 Ω. The power consumption of the electromagnets ranges from 0.25 to 0.41 W / 0.11 to 0.18 W and their total power dissipation ranges from 0.46 to 0.6 W. To sum up, the smaller electromagnet generated the same amount of magnetic moment with a shorter cable and less resistance resulting in lower power consumption. The battery should supply 180 mA / 140 mA current per hour in constant / sinusoidal modes. The lithium polymer battery, which fits beneath the circuit, provides around 700 mA of power and lasts for 3.5 hours if the device constantly used. The solenoid driver may also be powered and charged through the mobile device itself.

CONCLUSION

In this paper, we have proposed the use of frequency-modulated electromagnets instead of permanent magnets, as an input medium for Magitact, for sensing simultaneous around-device gestures via tracking multiple magnetic tokens. This enabled the possibility of bimanual and collaborative settings, which were not supported by Magitact. Furthermore, we introduced a novel input device, referred to as electromagnetic stylus, together with its hardware design specifications and conducted a user study, which shows that multiply electromagnetic styli can reliably be recognized using a single magnetic field sensor. Separating the magnetic signals produced by different sources eliminates dynamic noises within the magnetic field, which are caused by external conditions such as signal interference. The proposed method enhances the application space of existing mobile devices equipped with a magnetometer, without imposing any change in their hardware or physical specifications. Future mobile devices can be embedded with magnetometers having better sampling rate or sensitivity, in order to improve the capabilities of the proposed method. Finally, we think that special earphones can be designed to act as electromagnetic styli, in order to remove the necessity of an additional peripheral as an input device for the proposed method.

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REFERENCES

1. Ashbrook, D., Baudisch, P., & White, S. Nenya: Subtle and Eyes-Free Mobile Input with a Magnetically-Tracked Finger Ring. In *Proc. CHI 2011.* ACM Press (2011), 2043-2046.
2. Bianchi, A., & Oakley, I., MagnID: Tracking Multiple Magnetic Tokens. In *Proc. TEI 2015*. ACM Press (2015), 61-68.
3. Butler, A., Izadi, S., & Hodges, S. SideSight: Multi-'touch' interaction around small devices. In *Proc. UIST'08.* ACM Press (2008), 201-204.
4. Buxton, W. A Three-State Model of Graphical Input. In *Human-Computer Interaction* Vol. 90 (1990), 449-456.
5. Buxton, W. &, Myers, B. A study in two-handed input. In *CHI'86,* 321- 326.
6. Galyean, T. A. & Hughes, J.F. Sculpting: An Interactive Volumetric Modeling Technique. In *Proc. SIGGRAPH* Vol. 25, No. 4, ACM Press (1991), 267-274.
7. Guiard, Y. Asymmetric Division of Labor in Human Skilled Bimanual Action: the Kinematic Chain as a Model. In *The Journal of Motor Behavior* Vol. 19, 486–517.
8. Harrison, C. & Hudson, S.E. Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices. In *Proc. UIST'09,* ACM Press (2009), 121-124.
9. Hinckley, K., Pierce, J., Sinclair, M. & Horvitz, E. Sensing techniques for mobile interaction. In *Proc. UIST'00*, ACM Press (2000), 91-100.
10. Hinckley, K., Pausch, R., Goble, J.C. and Kassell, N.F. A survey of design issues in spatial input. In *Proc. UIST'94*, ACM Press (1994), 213-222.
11. Ketabdar, H., Yuksel, K.A. & Roshandel, M. MagiTact: Interaction with Mobile Devices Based on Compass (Magnetic) Sensor. In *Proc. IUI 2010,* ACM Press (2010), 413-414.
12. Ketabdar, H., Roshandel, M. & Yuksel, K.A. Towards Using Embedded Magnetic Field Sensor for Around Mobile Device 3D Interaction. In *Proc. MobileHCI 2010,* ACM Press (2010), 154-156.
13. Ketabdar, H., Roshandel, M. & Yuksel, K.A. MagiWrite: towards touchless digit entry using 3D space around mobile devices. In *Proc. MobileHCI 2010,* ACM Press (2010), 154-156.
14. Ketabdar, H., Yuksel, K.A., Jahnbekam, A., Roshandel, M. & Skripko, D. MagiSign: user identification / authentication based on 3D around device magnetic signatures. In *Proc. UBICOMM 2010,* IARIA, 31-34.
15. Liang, J. & Green, M. (1994). JDCAD: A Highly Interactive 3D Modeling System. In *Proceedings of he Computers & Graphics*, 18(4), 499-506.
16. Liang, R. H., Kuo, H. C., Chan, L., Yang, D. N., & Chen, B. Y., GaussStones: shielded magnetic tangibles for multi-token interactions on portable displays. In *Proc.* UIST'14. ACM Press (2014), 365-372.
17. Ni, T. & Baudisch, P. Disappearing mobile devices. In *Proc. UIST'09*. ACM Press (2009), 101-110.
18. Nyquist, H. Certain topics in telegraph transmission theory, In *Trans. AIEE*, Vol. 47, 617–644.
19. Rohs, M. & Kratz, S. Hoverflow: expanding the design space of around-device interaction. In *Proc. MobileHCI 2009,* ACM Press (2010), 1-8.
20. Sachs, E., Roberts, A. & Stoops, D. 3-draw: A tool for designing 3D shapes. In *IEEE Computer Graphics and Applications* (1991), 11(6), 18-26.
21. Shannon, C.E. Communication in the presence of noise. In *Proc. Institute of Radio Engineers*, Vol. 37, 10–21.
22. Voelcker, H.B. Demodulation of single-sideband signals via envelope detection. In *IEEE Trans. Communication Technology*, 22-30.
23. Yuksel, K. A., Ketabdar, H. & Roshandel, M. Towards digital music performance for mobile devices based on magnetic interaction, In *Proc. HAVE 2010*, IEEE Press (2010), 1–6.