MAGIC-Surfaces: Magnetically Interfaced Surfaces for Smart Space Applications

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Abstract. *This paper describes a new device for the easy construction of smart spaces. Based on a magnetic method, the device can provide non-contact, bi-directional communication as well as location and orientation estimation for indoor objects. An initial experimentation shows that the device can determine location and orientation with an accuracy of about 5 mm and 5 degrees, respectively.*

1. Introduction

One attractive application of pervasive computing is a smart space that supports human activity through embedded computer networks and sensors. Generally, smart spaces need to provide wireless network connectivity as well as location and orientation detection as basic functions. Sensor systems, human interfaces, and software platforms are built on these functions to provide high-level services. So far, various smart spaces have been built in the world. However, to provide the basic functions, almost all smart spaces are made by simply combining off-the-shelf or handmade devices. As a result, constructed testbeds usually do not look "smart" because the devices and cables are visible to users. Since a living space is usually made from building materials, we believe that it is necessary to make building materials smart to construct a true smart space that embodies Wiser's vision [1].

From this point of view, we have researched how to make such "smart building materials." Through our research, we found that general living spaces are made mainly from a combination of pillars and boards. Thus, we can construct true smart spaces if we integrate the necessary functions into the building materials. As one approach to this challenge, we propose "MAGIC-Surfaces (Magnetically Interfaced Surfaces)" that can provide the abovementioned functions of wireless network connectivity as well as location and orientation detection based on a magnetic method.

There have been previous works that tried to make surfaces smart in various approaches. Pushpin Computing [2] and Pin&Play [3] provide electric power by using layerd conductive sheets, and support bidirectional communication. The concept of these approach is similar to our work. However, they do not integrate localization function into original designs of their devices. Networked Surfaces [4] provides electric power and high-speed wired connection to various devices through small metallic plates located on the surface. This technology also detects the location and orientation of the devices [5]. However, a serious disadvantage of this technology is that the objects must contact the metallic plates on the surfaces. In many cases, a non-contact system is preferable since sometimes a plastic coating is applied on surfaces in a room environment. Smart Table [6] detects IDs, locations, and orientations of movable objects on a table by recognizing the magnetic footprints of the objects. However, it does not support bi-directional communication between the table and the objects. Sensetable [7] provides both localization and orientation detection of objects by using electromagnetic tablet. Since their system is mainly focused on user interface technology, it can provide accurate tracking of objects. However, bidirectional communication between the Sensetable and object is not integrated into the system.

In contrast to these devices, MAGIC-Surfaces can provide bi-directional communication along with localization and orientation detection in a non-contact manner. The following sections introduce the theoretical design and initial experimentation of MAGIC-Surfaces.

2. MAGIC-Surfaces

Figure 1 shows the system architecture of MAGIC-Surfaces. A MAGIC-Surface consists of an array of small magnetic communication devices. Each device has a microcoil and an electronic compass. The microcoil produces a magnetic field and is used as a transmitter. The electronic compass detects both the magnitude and direction of the magnetic field. Magnetic communication between the MAGIC-Surface and a movable device is provided by using a data modulated magnetic field.

The location and orientation of the movable device are determined as shown in Figure 2. In this figure, we assume that the locations of electronic compasses S_1 and S_2 are known, and the orientation of coil L_1 is zero for simplicity. When we turn on the current to L_1, a magnetic field is produced on the sensors. Here, we consider the magnetic field at S_1 as a radial component B_{r_1} and a tangential component B_{θ_1}. Based on the theory of magnetic dipoles, we can formulate the magnitude of each vector with the following equations:

$$B_{r_1} = \frac{\mu_0}{2\pi}(nI\pi a^2)\frac{cos\theta_1}{r_1^3} \quad (1)$$

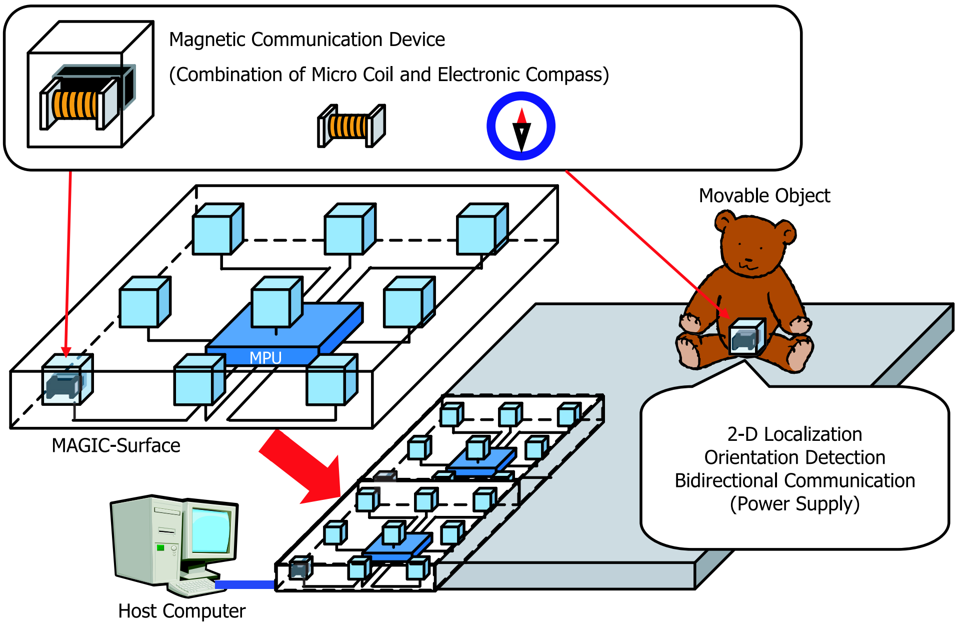


Figure 1. System Architecture

$$B_{\theta_1} = \frac{\mu_0}{4\pi}(nI\pi a^2)\frac{sin\theta_1}{r_1^3} \tag{2}$$

Here, μ_0 is the permeability in free space, n is the number of turns of the coil, I is the current, and a is the radius of the coil. In our example, the electronic compass S_1 indicates an angle δ_1 of the vector B_{S_1}, which is the sum of the two vectors, B_{r_1} and B_{θ_1}. Let's consider $\phi_1 = \delta_1 - \theta_1$. Then, ϕ_1 can be described as:

$$tan\phi_1 = \frac{B_{\theta_1}}{B_{r_1}} = \frac{1}{2}tan\theta_1 \tag{3}$$

Here, $tan\phi_1$ is also expressed as:

$$tan\phi_1 = tan(\delta_1 - \theta_1) = \frac{tan\delta_1 - tan\theta_1}{1 + tan\delta_1 tan\theta_1} \tag{4}$$

Therefore, by measuring δ_1, we can compute θ_1 as follows:

$$\theta_1 = tan^{-1}(\frac{-3 \pm \sqrt{9 + 8(tan\delta_1)^2}}{2tan\delta_1}) \tag{5}$$

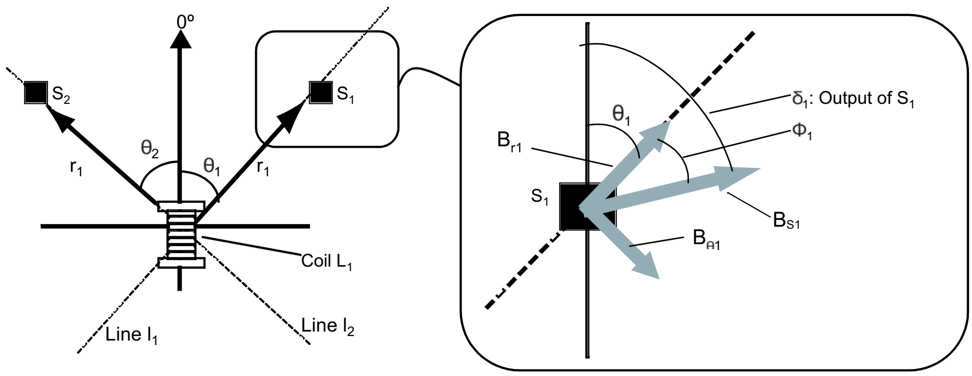


Figure 2. Detection of Location and Orientation

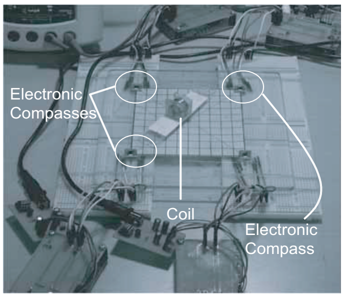
If the two angles, δ_1 and δ_2, are obtained from the output of the electronic compasses, S_1 and S_2, we can determine the location of the coil as the intersection of the two lines, l_1 and l_2. In general, we cannot assume that the orientation of the coil is always zero. In this case, by using three or more electronic compasses, we can determine the location and orientation of the coil based on Newton's method. In this way, MAGIC-Surfaces can determine the location and the orientation of movable objects.

3. Experimentation

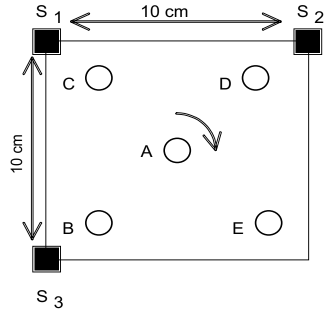
To confirm the abovementioned theoretical design, we performed an experiment, as shown in Figure 3 (a). In this experiment, four electronic compasses were located at the corners of a 10 cm $\times$ 10 cm square. A 200-turn coil was used to produce the magnetic field, and a 120-mA, 3-kHz sinusoidal current source was connected to the coil.

First, we measured the accuracy of the localization at test points A-E, as shown in Figure 3(b). Depending on the geometry of the electronic compasses and the coil, the accuracy of localization varied from 1 mm to 6 mm (Figure 3(c)). This result indicates that we should carefully design an electronic compass selection algorithm in actual MAGIC-Surfaces to achieve highly accurate localization. Next, we measured the accuracy of the orientation detection at measurement point A (Figure 3(d)). This result shows that we can determine the orientation of the coil with an accuracy of 5 degrees or less. Note that we also confirmed that the level of the received signal at each electronic compass is sufficient for magnetic communication.

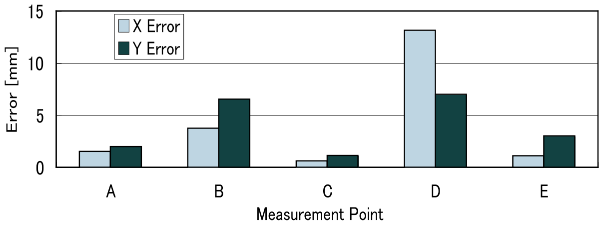
Although the above results show that our device has the potential to



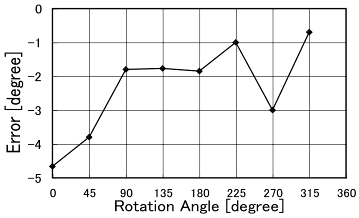
(a) Experimental Setup



(b) Measurement Points



(c) Location Estimation Error



(d) Orientation Estimation Error

Figure 3. Experimentation

provide highly accurate localization and orientation detection, detailed experimentation and error analysis are further required to specify any essential problems that can degrade the performance of MAGIC-Surfaces.

4. Summary

This paper introduced MAGIC-Surfaces, a device that enables short-range, bi-directional communication with and localization and orientation detection for smart space applications based on a magnetic method. Experimental results showed that the system can determine location and orientation with an accuracy of about 5 mm and 5 degrees, respectively. Despite the success of our initial experimentation, there remain several important problems. Basically, we think the major advantage of our device is its non-contact property. However, as introduced in [8], magnetic communication technology has other interesting advantages, especially in near-field communication systems. Therefore, an important future work is to find a good application scenario that emphasizes the merits of the magnetic method. On the technical side, It is important to design a control protocol that integrates magnetic communication with localization and orientation detection. It is also important to design an auto-configuration mechanism to enhance deployment scalability of the system. In addition, Low power consumption, miniaturization and robustness are important goals for practical applications. We expect that printable electronics technology will be a good solution for such problems.

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