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Dipole Estimation from the Magnetic Field Gradient for RFID Tag Localization†

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This paper presents a simple sensor and algorithm to estimate the position of a magnetic dipole for localization of an RF-ID tag. Acquisition of the tag position, in addition to the ID information, opens up various applications with location awareness. A key point of our method is the use of spatial gradients of the magnetic field, created by the RF-ID tag. First we show a deterministic algorithm to express the tag position, irrespective of its posture, in terms of the combination of the fields and their first order spatial derivatives. Then, we show a sensor unit that can measure the spatial gradients efficiently.

Key Words: RF-ID tag, localization, inverse problem, source identification, complex gradients

1. Introduction

Recently, Radio Frequency Identification (RFID) tags have attracted great attention as a key device in various domains, such as ubiquitous computing, tracking of physical objects, robotics, human-machine interfaces, and so on. In those systems, acquisition of the location information of the RFID tags, in addition to their ID number, opens up various applications. For example, navigations for the blind [1], mobile robots [2] [3], a person in a house [4] are easily realized by detecting the position of RFID tags. Services to patients [5] or athletes according to their locations are other potential domains.

There have been several researches on tag localization so far. Siio [6] developed a tag-pasted floor for position detection such that one of 100 RFID tags on the 1.5m by 1.5m floor was detected by an RFID reader equipped with a foot-wear device. The frequency band used was 135 kHz. Kantor *et.al.* [3] used RFID tags for localization of a mobile robot. Given a map of the environment, the location of the robot was reconstructed using range data from tags whose position were known on the map. They extended the method to the problem of simultaneous localization and mapping (SLAM) using a Kalman filter. Hähnel [2] proposed a probabilistic method with laser range data and RFID tags.

Localization of RFID tags can be considered an inverse source problem of electromagnetic fields. Naturally, an active type RFID tag is the source of the field. Even the passive type is regarded as a secondary source that creates fields at the reader site.

In this paper, we present a simple sensor and algorithm for this inversion. Our method is based on measurement of the spatial derivatives of the magnetic field. First, we show an algorithm and a sensor unit for the near field, where the driving frequency is relatively low such that the wavelength is much larger than the distance from the source to the sensor. The RFID tags with 135 kHz or 13.56 MHz are the case. Although the field can be detected within a distance of 500 mm from the source, there still exist various 'desktop' applications such as localization of a fingertip for tactile display, localization of an object in a showcase in a shop/museum, and so on. In this paper, for the near field, we consider a restricted situation in which the depth and posture of the source are fixed. Second, we show an algorithm and design a sensor unit for the far field. The RFID tags with the driving frequency of 2.45 GHz are the case. The algorithm can reconstruct the 3D position of the source whatever the orientation of the tag.

2. Estimation from the near field

2.1 Theory

The loop antenna in the RFID tag is regarded as a mag-

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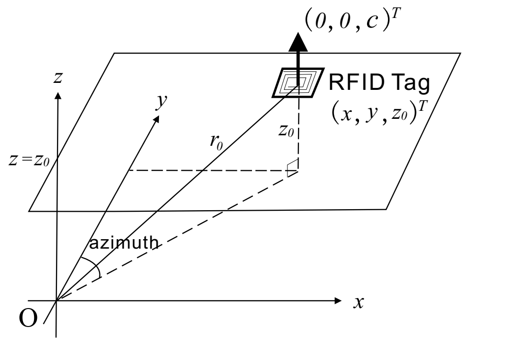

Fig. 1 A problem setting for measuring a near field

netic dipole. Denote its moment and the location by $\boldsymbol{m}\,\mathrm{e}^{-i\omega t} = (a, b, c)^T \mathrm{e}^{-i\omega t}$ and $\boldsymbol{r} = (x, y, z)^T$, respectively, and suppose that a magnetic sensor is located at the origin. Then, the induction magnetic field in the near zone is expressed as [7)]

$$\boldsymbol{H} = \frac{1}{4\pi} \frac{3\boldsymbol{n}(\boldsymbol{n} \cdot \boldsymbol{m}) - \boldsymbol{m}}{r^3}, \tag{1}$$

where $r = |\boldsymbol{r}|$, $\boldsymbol{n} = \frac{\boldsymbol{r}}{r}$. The term $\mathrm{e}^{-i\omega t}$ is omitted.

In this paper, for the near field, we consider a restricted, but useful case: a planar loop coil in the RFID tag moves on the plane, $z = z_0$, while keeping the orientation of the moment parallel to the z-axis, $\boldsymbol{m} = (0, 0, c)^T$, as shown in **Fig. 1**. Such a situation occurs, for instance, when an object on a desk in a showcase is to be localized. The depth z_0, which is the distance from a sensor to the desk plane, is assumed to be known.

Consider the measurement of the spatial derivatives of H_z with respect to the x and y directions. From Eq. (1), these components are expressed as

$$\frac{\partial}{\partial x} H_z = \frac{1}{4\pi} \left(-15 \frac{c z_0^2}{r_0^5} + 3 \frac{c}{r_0^3} \right) x, \tag{2}$$

$$\frac{\partial}{\partial y} H_z = \frac{1}{4\pi} \left(-15 \frac{c z_0^2}{r_0^5} + 3 \frac{c}{r_0^3} \right) y, \tag{3}$$

where

$$r_0 \equiv \sqrt{x^2 + y^2 + z_0^2} \tag{4}$$

is the distance from the source to the sensor. One finds that although Eqs. (2) and (3) are nonlinear functions of the source location, the ratio of $\frac{\partial}{\partial x} H_z$ to $\frac{\partial}{\partial y} H_z$:

$$\frac{\frac{\partial}{\partial x} H_z}{\frac{\partial}{\partial y} H_z} = \frac{x}{y} \tag{5}$$

simply represents the azimuthal angle of the source. The elevation angle is obtained from

$$H_z = \frac{1}{4\pi} \left(3 \frac{c z_0^2}{r_0^5} - \frac{c}{r_0^3} \right) \tag{6}$$

for the fixed depth z_0.

Thus, measuring H_z, $\frac{\partial H_z}{\partial x}$, $\frac{\partial H_z}{\partial y}$ with the known depth z_0 determines the location of the source. The spatial derivatives of the magnetic field, $\frac{\partial H_z}{\partial x}$, $\frac{\partial H_z}{\partial y}$ can be measured by planar gradiometers consisting of planar oppositely wound coils as in **Fig. 2**. Therefore, three planar coils consisting of a simple loop coil for H_z, and gradiometers for the x and the y directions, $\frac{\partial H_z}{\partial x}$, $\frac{\partial H_z}{\partial y}$, can realize direct localization of the magnetic dipole in this case.

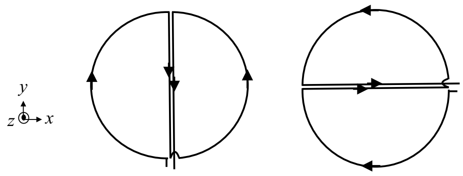

Fig. 2 Planar gradiometers consisting of planar oppositely wound coils for measuring $\frac{\partial H_z}{\partial x}$ (left) and $\frac{\partial H_z}{\partial y}$ (right)

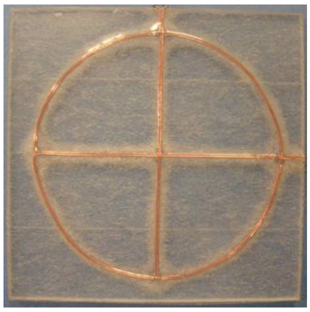

Fig. 3 The sensor unit consisting of a loop coil for measuring H_z and two gradiometers for measuring $\frac{\partial H_z}{\partial x}$ and $\frac{\partial H_z}{\partial y}$

2.2 Experiment

We show a localization experiment in a restricted case where the posture and the depth of the source are fixed. Fig.3 depicts the planar sensor unit consisting of a loop coil for measuring H_z and two gradiometers for measuring $\frac{\partial H_z}{\partial x}$ and $\frac{\partial H_z}{\partial y}$. As a source magnetic dipole modeling an RFID tag, a loop coil with a diameter of 1 cm as in Fig.4 is used. The driving frequency is 1 MHz.

Fig. 5 and **Fig. 6** depict the theoretical and experimental output of the loop coil for measuring H_z, and of the gradiometer for measuring $\frac{\partial H_z}{\partial x}$, respectively, where the source with $y = 50$ mm and $z = 100$ mm moves along the x-axis, in the Fig. 1 situation. **Fig. 7** shows the estimation result of the azimuth angle of the source, calculated by

$$\theta = \arctan \frac{\frac{\partial H_z}{\partial x}}{\frac{\partial H_z}{\partial y}}. \tag{7}$$

It is confirmed that the azimuth is reconstructed well for a ± 60 degree range. The 2D position on the xy-plane can be reconstructed using Fig. 5 and Fig. 7.

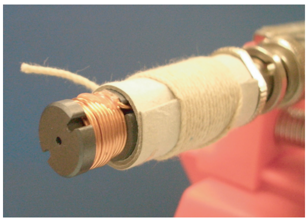

Fig. 4 A source loop coil

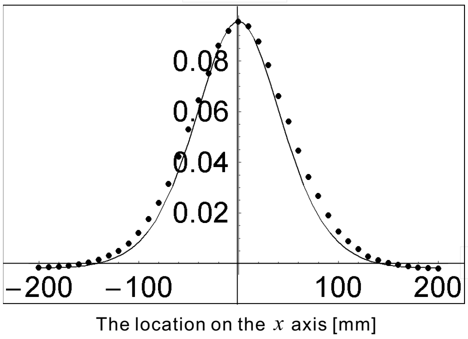

Fig. 5 Theoretical and experimental output of the loop coil for measuring H_z, where $y = 50$ mm and $z = 100$ mm

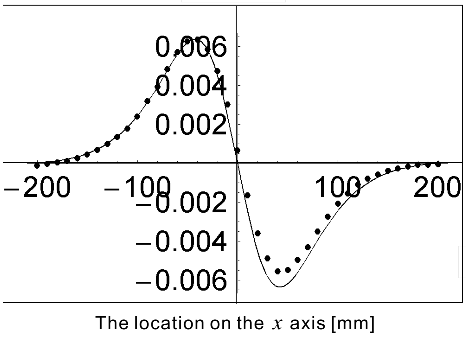

Fig. 6 Theoretical and experimental output of the gradiometer for measuring $\frac{\partial}{\partial x}H_z$, where $y = 50$ mm and $z = 100$ mm

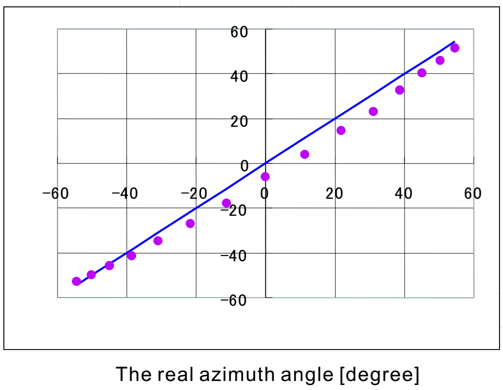

Fig. 7 Estimation of the azimuth angle of the source, where $y = 50$ mm and $z = 100$ mm

3. Estimation from the far field

3.1 Theory

When the frequency is high such that $kr \gg 1$, the far field is dominant. Modeling a dipole antenna in an RFID tag by the electric dipole $\boldsymbol{p}\,\mathrm{e}^{-i\omega t} = (a, b, c)\mathrm{e}^{-i\omega t}$ located at $\boldsymbol{r}$, the radiation field measured at the origin is expressed as [7]

$$\boldsymbol{H} = \frac{i\omega}{4\pi}(\boldsymbol{n} \times \boldsymbol{p})\frac{\mathrm{e}^{ikr}}{r}. \tag{8}$$

We propose to observe the following quantities:

- $H_x + iH_y$ (9)
- $\left(\frac{\partial}{\partial x} + i\frac{\partial}{\partial y}\right)(H_x + iH_y)$ (10)
- H_z (11)
- $\frac{\partial}{\partial z}H_z$ (12)

Eq. (9) represents the combination of the x- and y-components, in complex form, of the magnetic field. Eq. (10) substantially consists of four components: $\frac{\partial H_x}{\partial x}, \frac{\partial H_x}{\partial y}, \frac{\partial H_y}{\partial x}, \frac{\partial H_y}{\partial y}$. We call the gradient in the form of $\frac{\partial}{\partial x} + i\frac{\partial}{\partial y}$ a complex gradient.

Eqs.(9)-(12) are written by the source position and moment as

$$H_x + iH_y = i\frac{c(x + iy) - (a + ib)z}{r^2}\mathrm{e}^{i(kr-\omega t)}, \tag{13}$$

$$\left(\frac{\partial}{\partial x} + i\frac{\partial}{\partial y}\right)(H_x + iH_y) = (2 - ikr)\,R\,(H_x + iH_y), \tag{14}$$

$$H_z = \frac{ay - bx}{r^2}\mathrm{e}^{i(kr-\omega t)}, \tag{15}$$

$$\frac{\partial}{\partial z}H_z = -(2 - ikr)\zeta H_z, \tag{16}$$

where

$$R = \frac{x + iy}{r^2}, \tag{17}$$

$$\zeta = \frac{z}{r^2}. \tag{18}$$

R and ζ represent the transformed 3D position of the source. In fact, R and ζ can be interpreted as the source projected position on the Riemann sphere, and the third coordinate value of the source, respectively [8].

Consequently, by combining Eqs. (13), (14) and Eqs. (15), (16), we have

$$\frac{\left(\frac{\partial}{\partial x} + i\frac{\partial}{\partial y}\right)(H_x + iH_y)}{H_x + iH_y} = (2 - ikr)R, \tag{19}$$

$$\frac{\frac{\partial}{\partial z}H_z}{H_z} = -(2 - ikr)\zeta. \tag{20}$$

Thus, from Eqs. (19), (20), we arrive at

$$\frac{R}{\zeta} = -\frac{\left(\frac{\partial}{\partial x} + i\frac{\partial}{\partial y}\right)(H_x + iH_y)}{H_x + iH_y} \cdot \frac{H_z}{\frac{\partial}{\partial z}H_z}. \tag{21}$$

From the definitions of R and ζ in Eqs. (17), (18), R/ζ is represented by the source position as

$$\frac{R}{\zeta} = \frac{x+iy}{z}. \tag{22}$$

Therefore, we can identify the azimuth and the elevation angle of the source, whatever the source posture $\boldsymbol{m}$.

In order to obtain the distance from the sensor to the source, we put the absolute value of the obtained ratio in Eq. (21) as

$$\alpha \equiv \frac{|R|}{\zeta}. \tag{23}$$

Since it holds that

$$|R|^2 + \zeta^2 = \frac{1}{r^2}, \tag{24}$$

the third coordinate, ζ, can be written as

$$\zeta = \frac{1}{\sqrt{1+\alpha^2}}\frac{1}{r}. \tag{25}$$

Substituting Eq. (25) into, for example, Eq. (20) yields

$$r = \frac{2}{ik - \sqrt{1+\alpha^2}\frac{\frac{\partial}{\partial z}H_z}{H_z}}. \tag{26}$$

Thus, the sensor-source distance is obtained. In this way, the RFID tag location is determined from the complex gradients of the magnetic field at the reader site, irrespective of the tag posture.

3.2 Design of a sensor unit

For the general case where the 3D location and the posture of the source are unknown, we measure $H_x, H_y, H_z, \frac{\partial H_x}{\partial x}, \frac{\partial H_x}{\partial y}, \frac{\partial H_y}{\partial x}, \frac{\partial H_y}{\partial y}, \frac{\partial H_z}{\partial z}$. **Fig. 8** depicts the design of the antenna in the RFID reader to detect them. The relationships between $V_1 \sim V_8$ and the fields are as follows:

$$V_1 \propto H_x, \quad V_2 \propto \frac{\partial H_x}{\partial y}$$
$$V_3 \propto H_y, \quad V_4 \propto \frac{\partial H_y}{\partial x}$$
$$V_5 \propto H_z, \quad V_6 \propto \frac{\partial H_x}{\partial x}$$
$$V_7 \propto \frac{\partial H_y}{\partial y}, \quad V_8 \propto \frac{\partial H_z}{\partial z}$$

In the figure, loops for $V_1 \sim V_5$ and for $V_6 \sim V_8$ are separately depicted, but they in fact are placed in a single sphere.

4. Conclusion

We proposed a simple sensor and algorithm to estimate the position of the magnetic field source from the spatial gradients of a field for localization of RFID tags. For the near field, we showed the azimuth and the elevation angle of the source were directly reconstructed by planar coils in a restricted situation where the posture and the depth of the tag were fixed. For the far field, we showed that a certain combination of the first order spatial gradients and the field values determined the azimuth and the elevation angle, whatever the posture of the tag.

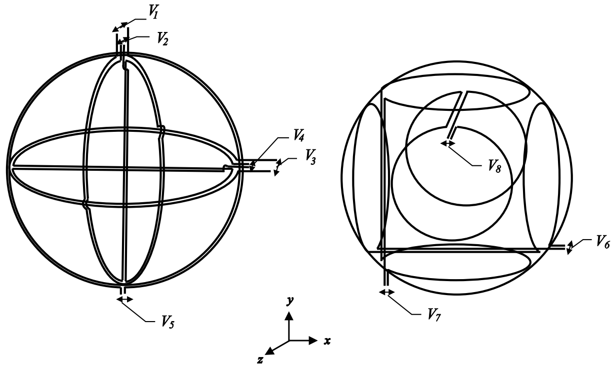

Fig. 8 Design of the antenna in the RFID reader (Loops for $V_1 \sim V_5$ and ones for $V_6 \sim V_8$ are separately depicted. In fact, the 8 loops are wound in a single sphere.)

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