Wireless orientation sensing using magnetoquasistatic fields and complex image theory

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Abstract— **In this paper we report on a magnetoquasistatic orientation sensor that uses the magnetoquasistatic coupling between an electrically small emitting loop (magnetic dipole) and seven vertical receiving loops located on a circle of radius 12.19 m to determine the orientation of an object. By inverting the theoretical expression for the coupling between the emitter and receivers and using complex image theory, we are able to estimate the azimuthal orientation, ϕ, and inclination orientation, θ, of the emitter from the received fields. We achieved an average error of 5.93° and 10.66°, respectively, and a median error of 4.08° and 8.68°, respectively.**

I. INTRODUCTION

Wireless positioning sensors play a key role in tracking and monitoring of remote systems. Many position location sensing systems use line-of-sight (LoS) signaling to achieve position information. Examples include ultra-wideband (UWB), global positioning (GPS), and radio-frequency identification (RFID) systems. While these can be very accurate, determination of the orientation of a fixed-position object would require either an internal orientation sensor whose output is communicated through an RF link to a receiver or multiple sensors distributed over an object in order for the receiver to determine the orientation of the object from ranging/distance measurements. Moreover, the above mentioned systems can suffer from multi-path effects and generally require a LoS [1], making them less viable in many environments where a LoS is not practical. Examples of applications within such environments include but are not limited to the determination of part orientation in the manufacturing industry [2], and in aiding grasp planning in the robotics industry [3], where location information is often known and orientation information is required.

In this work, we investigate the use of magnetoquasistatic fields generated by a small current loop to sense the orientation of an object. The non-uniform spatial profile of the magnetic field created by a current loop provides a means to directly measure orientation by measuring the field amplitude at multiple locations. By operating in the quasistatic regime, very little energy is radiated by the dipole while still allowing the field to be sensed from distances of tens of meters. In addition, quasistatic magnetic fields are largely unperturbed by weakly conducting dielectric bodies and work well in non-line-of-sight (NLoS) environments.

To accurately determine the orientation of a dipole, we need to consider not only the fields generated directly by the dipole, but also the fields generated by its image in the earth. Recently, we introduced a distance sensing technique that uses complex image theory to account for the fields generated by the dipole image in the weakly conducting earth [4], [5]. In our previous work, we measured the magnetic field from an emitting magnetic dipole (an electrically small loop) using a receiving loop, and inverted the theoretical expression to determine distance. We used a frequency on the order of a few hundred kilohertz to obtain the required signal-to-noise ratio (SNR) and used complex image theory [6] to correct for the ground effect. This resulted in an estimated distance accuracy of better than 24 cm for distances up to 34.2 m between the emitter and receiver (one-dimensional, 1-D) along a direction perpendicular to the surface normal of the loops. At short distances, we showed that this error can be significantly reduced by including a more accurate description of the fields of a loop [7].

In this paper, we report a new orientation sensor that leverages the approach of our magnetoquasistic distance sensor technique to accurately measure the orientation of a remote object. Section II presents a brief overview of complex image theory and our approach for orientation sensing. In Section III, we present a description and result of our orientation sensing experiment. Section IV provides concluding remarks.

II. COMPLEX IMAGE THEORY AND ORIENTATION SENSING

Within the quasistatic region of an electromagnetic source located at a height $z = h$ above the earth, the magnetic field above the earth ($z > 0$) is approximated by [6]

$$\vec{H}_p(x, y, z) \approx \vec{H}_p^s(x, y, z) + c_p \vec{H}_p^i(x, y, z), \tag{1}$$

where the first and second terms on the right hand side are the fields of the source and complex image of the source, respectively. The subscript $p = ||, \perp$ describes components parallel and perpendicular to the ground, respectively; the superscripts s and i denote the source and the complex image, respectively; and $c_{||} = 1$ and $c_{\perp} = -1$. For a magnetic dipole source, the magnetic fields of the source and the complex image are $\vec{H}^s(x, y, z) = \vec{H}^d(x, y, z-h)$ and $\vec{H}^i(x, y, z) = \vec{H}^d(x, y, -z-h-\delta(1-j))$, where $\vec{H}^d(x, y, z)$ is the magnetic field of a magnetic dipole at the origin [8], and $\delta = \sqrt{1/\pi f \mu \sigma}$ is the skin depth, where f is the oscillation frequency of the source field, μ is the permeability of the

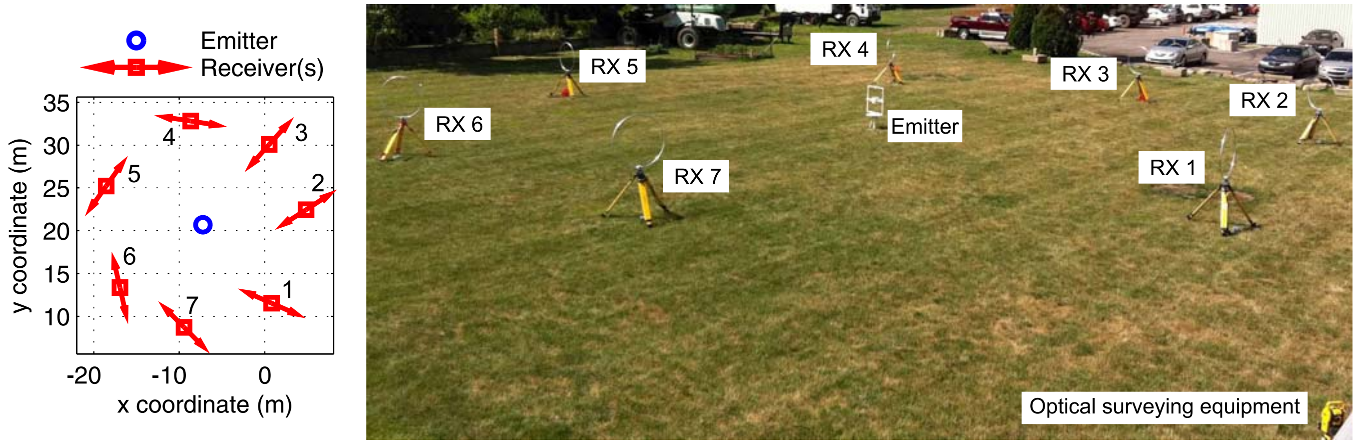


Fig. 1. Experimental setup for the spherical system orientation ϕ (azimuthal angle) and θ (inclination angle) measurement of the emitting loop. The figure on the left indicates the optical ground truth positions and orientations of the emitter and receivers.

earth and σ is the conductivity of the earth. The voltage measured at the terminals of a receiving loop can be found from Faraday's law, and is given by

$$V = -j(2\pi f)\mu_o \left[\hat{n} \cdot \left(\vec{H}_{||} + \vec{H}_{\perp}\right)\right] a_r, \tag{2}$$

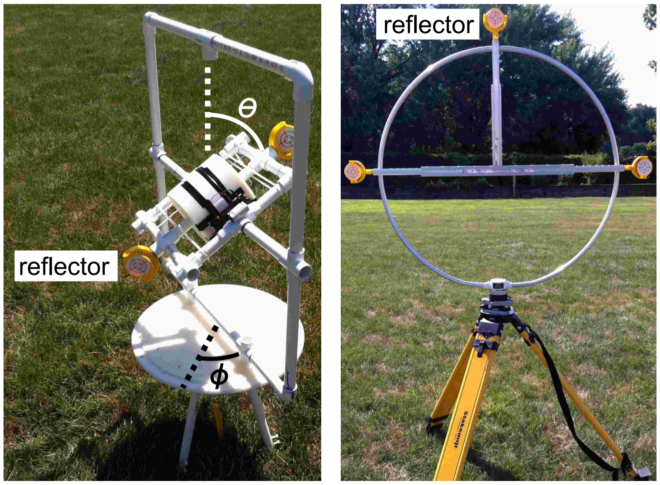
where $\hat{n}$ is the surface normal unit vector of the receiving loop, and a_r is the surface area of the receiving loop.

To solve for the spherical system azimuthal angle, ϕ, and inclination angle, θ, one must know *a priori* the x, y, and z coordinate of the emitting loop, use a minimum of $k \geq 2$ receivers located diversely, and know the position and orientation of all receivers. The optimal solution for ϕ and θ can be found by minimizing the difference between the value of the theoretical voltage, V_l^T, and measured voltage, V_l^M, at the terminals of all loops, where $l = 1, \ldots, k$ denote each receiving loop. This can be done by using a numerical, non-linear, least-square optimization algorithm to minimize

$$\Phi = \sum_{l=1}^{k} \left[V_l^T - V_l^M\right]^2 . \tag{3}$$

III. DESCRIPTION OF EXPERIMENT

In our previous positioning work, [5], multiple receivers where used outside a grid to measure the fields of the emitting loop positioned on the grid, and the position of the emitter was found by inverting the theoretical expression for the measured values at each receiver by minimizing (3) for known orientation of the emitting loop. For our proposed orientation sensor, we use multiple receivers to measure the fields of a fixed position emitter (distance from receivers known *a priori*) at step increments of orientations ϕ and θ, and minimize (3) to find the orientation of the emitting loop. The emitting loop is located at the center of a circle of radius 12.19 m, and seven receiving loops were spaced evenly on the circle, as shown in Fig. 1. An optical surveying instrument with built-in electronic distance measurement, shown at the bottom right of Fig. 1, was used to measure the position and orientation of both the emitter and receiver. The actual positions and orientations of the emitter and each receiver are shown on the plot on the left of Fig. 1, where the arrows on the receivers denote the surface normal direction of the loops. Figure 2 shows the setup for the emitting and receiving loops. The emitting loop tripod setup in Fig. 2a is similar to that used in [5], constructed out of Delryn/Acetal (polyoxymethylene), with the key difference being a structure constructed of polyvinyl chloride (PVC) pipe to enable arbitrary orientations ϕ and θ. The actual position and orientation of the emitter and each receiver are obtained through optical measurements of the mounted reflectors, shown in Fig. 2, using the surveying instrument. The receiving loop in Fig. 2b is a 1 m diameter LFL-1010 active receiving loop, from Wellbrook Communications,



(a) (b)

Fig. 2. The emitting loop (a) connected to the oscillator circuit and two reflectors, and the receiving loop (b) mounted on a fiberglass surveying tripod and connected to three reflectors [5]. The reflectors are used for position and orientation ground truth measurements.

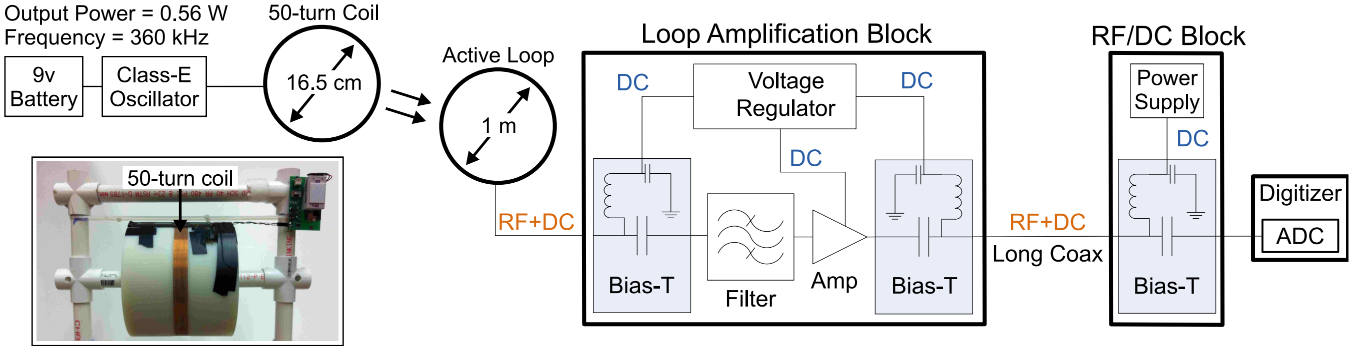


Fig. 3. Emitter and receiver block diagrams with an active receiving loop, filter, and RF amplification circuit. The figure in the inset shows the unenclosed 50-turn emitting loop connected to the class-E oscillator and driven by a 9V battery [5].

mounted above a fiberglass surveying tripod. The mounting structure for the three reflectors in Fig. 2b is used to obtain an accurate position and orientation ground truth of the receivers, and is removed prior to RF measurements. The reader is referred to [5] for a detailed description of the mechanical construction of the system. Figure 3 presents a block diagram of the measurement setup for the emitter and for each receiver. The emitting loop consists of 50-turns of 34 American Wire Gauge (AWG) wire coiled with a diameter of 16.5 cm, and fed using a battery-operated class-E oscillator with an oscillation frequency of 360 kHz and output power of 0.56 W. The receiver system consists of the active receiving loop, a band-pass filter to attenuate unwanted signals (passband region of 300 kHz to 450 kHz), an ultra-low-noise amplifier (AD8331 by Analog Devices), and a 16-bit ADC to digitize the signal. The reader is again referred to [5] for a detailed description of the electrical construction of the emitting and receiving system.

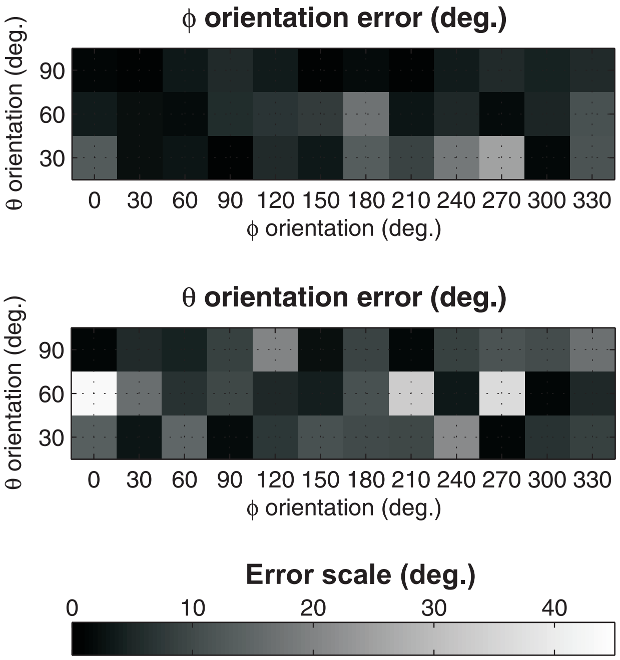


Fig. 4. Estimated error for orientation ϕ (azimuthal angle) and θ (inclination angle), defined as the absolute difference between the actual optically measured orientation and the estimated orientation using the magnetoquasistatic technique.

For the orientation measurement, the emitter azimuthal angle, ϕ, and inclination angle, θ, were varied, where ϕ and θ are defined in Fig. 2(a). The voltage was measured at the terminals of each of the seven receiving loops for orientations ϕ of 0° to 330° in steps of 30° and for θ of 30°, 60° and 90°. The position (x, y, z) of the emitter obtained from the optical ground truth measurements was used to reduce the number of unknowns in (2) to three: the orientation ϕ and θ of the emitting loop and the ground conductivity σ. A ground conductivity of $\sigma = 0.055$ S/m, which is within one order of magnitude of independent measurements [9], was chosen to obtain good agreement between the theory and measurements. The optimal solution for the estimated orientation was found by minimizing (3) for the coupling between the emitter and all receivers.

Figure 4 shows the absolute difference between the actual orientation measured using the optical instrument and the estimated orientation using our magnetoquasistatic technique. The figure at the top of Fig. 4 shows the ϕ orientation error and at the bottom shows the θ orientation error. Figure 5 shows the cumulative distribution function of the error for both ϕ and θ. The estimated ϕ and θ orientation derived from the measured fields result in an average error of 5.93° and 10.66°, respectively, and a median error of 4.08° and 8.68°, respectively.

Because vertical receiving loops were used (surface normal parallel to the earth), the highest sensitivity and lowest ϕ error occur when the emitter is also vertical, or $\theta = 90^\circ$. The system is least sensitive at $\theta = 0^\circ$ due to the azimuthal symmetry of the magnetic dipole field with respect to the receivers. By using two orthogonal loops on our emitter, we expect that this reduction in sensitivity with θ can be significantly reduced.

IV. CONCLUSION

In this paper, we present an orientation sensor system that is able to accurately measure the azimuthal and inclination

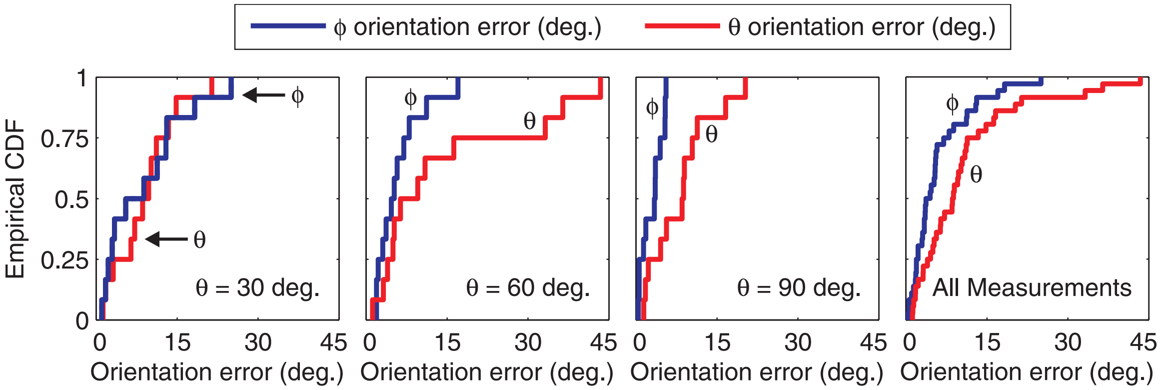


Fig. 5. Cumulative distribution function of errors. The average ϕ error is 5.93° and the average θ error is 10.66°, with median errors of 4.08° and 8.68°, respectively. The azimuthal error (ϕ) is least when the emitter is horizontal (θ=90°) and increases as it become more vertical (θ <90°).

angle of an object at a distance of 12.19 m with an average ϕ error of 5.93° and average θ error of 10.66°. We reduced the number of unknowns in the problem by using a known position. This would be valid in many applications, such as in determining part orientation within the manufacturing industry [2] and in aiding grasp planning in the robotics industry [3], where the orientation of a fixed object is desired. We expect the proposed quasistatic-based technique to excel over conventional propagation-based techniques in NLoS and multi-path environments, such as those present in the manufacturing or robotics industry. Extending this approach to the determination of orientation with unknown position is a topic of future research.

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