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Real-time magnetic dipole detection with single particle optimization

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ABSTRACT

In recent years, the use of magnetic field measurements has become relevant in several applications ranging from non-invasive structural fault detection to tracking of micro-capsules within living organisms. Magnetic measurements are, however, affected by a high noise due to a number of causes, such as interference from external objects and the Earth magnetic field. Furthermore, in many situations the magnetic fields under analysis are time-variant, for example because generated by moving objects, power lines, antennas, etc. For these reasons, a general approach for accurate real-time magnetic dipole detection is unfeasible, but specific techniques should be devised. In this paper we explore the possibility of using multiple 3-axis magnetic field sensors to estimate the position and orientation of a magnetic dipole moving within the detection area of the sensors. We propose a real-time Computational Intelligence approach, based on an innovative single particle optimization algorithm, for solving, with an average period of 2.5 ms, the inverse problem of magnetic dipole detection. Finally, we validate the proposed approach by means of an experimental setup consisting of 3 sensors and a custom graphical application showing in real-time the estimated position and orientation of the magnetic dipole. Experimental results show that the proposed approach is superior, in terms of detection error and computational time, to several state-of-the-art real-parameter optimization algorithms.

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Introduction

For many industrial applications it is desirable to obtain an accurate characterization of a ferromagnetic object (or a set of objects), by measuring the magnetic fields induced by it. Magnetic field detection can be used, for example, for identifying vehicles based on their magnetic profile, or for detecting defects, e.g. inner cracks or micro-holes, in metallic structures (rails, steel beams, etc.). Broadly speaking, all those applications which rely on the analysis of magnetic field measurements require that the magnetic dipoles (or in general, magnetic domains) present in the structure under study are precisely localized. In addition to that, in some cases it might be needed to detect a time-variant magnetic field in real-time, e.g. when one wants to track a magnetic dipole whose position and orientation change with time. A paradigmatic example of a real-time application of this kind would be a magnetic-based motion tracking system, where one or more dipoles are attached to a moving object and their position/orientation must be estimated online. Such a system could be used, for instance, in video gaming, motion capture, 3D painting, or interactive path-planning of industrial robots.

Despite the broad potential applications, the problem of detecting and interpreting magnetic fields in real-time still represents an open challenge. The reasons are manifold, namely: (1) the high noise which usually affects magnetic measurements; (2) the effect of the static earth magnetic field; (3) the interference due to the magnetic fields generated by surrounding electrical currents and objects, such as computers and other electronic devices; (4) the real-time constraints imposed by the sensor data acquisition frequency and, in case of moving magnetic dipoles, their speed.

In recent years, several methods have been developed for localizing magnetic dipoles, and have been applied to various contexts ranging from engineering to biomedicine. These methods are based, in general, on the solution of the inverse magnetic problem by means of different optimization strategies, such as Computational Intelligence algorithms or classic local search methods. In [1], an array of 3-axis magnetic sensors is used to track a magnet, modeled as a single dipole, inside a capsule endoscope for the interactive diagnosis of the gastrointestinal tract; in this case, the localization is solved by means of a combination of a linear localization algorithm [2] and the Levenberg–Marquart method [3], where the first provides a valid initial guess and the latter tries to improve upon it. In [4], the same authors extend this approach for detecting position and orientation of a rectangular magnet in a capsule endoscope by means of basic genetic algorithm (GA) [5] and particle swarm optimization (PSO) [6]. In both studies it was obtained, in

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simulation, a high localization/orientation accuracy and computational time in the order of tenths of a second – up to 2 s – depending on the desired accuracy. Paper [7] proposes a similar approach for tracking, by means of an adhesive magnet, the tongue movements within the 3-D oral space; in this case PSO was compared with three local search methods, namely the DIRECT [8], Powell [9], and Nelder–Mead [10] algorithms, with the Powell algorithm resulting in the highest accuracy and an average processing time of 43.9 ms/sample.

Some alternative approaches, which do not make use of an explicit optimization algorithm, have also been proposed in the literature. For example, in [11], a real-time localization technique is described, based on the Euler homogeneity equation. In [12], a Hopfield neural network [13] was applied to the estimation of magnetic moments, while a self-adaptive evolutionary algorithm was used for training the model by minimizing the least-squares error between the observations and the data produced by the neural network. Also in these cases, the proposed approaches display a high accuracy, a good robustness, and a relatively simple implementation.

Most of the methods from the literature, however, either make problem-specific assumptions or they are not suitable for fast real-time tracking of moving magnetic objects (i.e. in the order of few milliseconds per sample), because for instance they require an offline learning phase or an offline data processing. To fill this gap, in this paper we present a novel optimization-based method for fast detection of position and orientation of a single magnetic moment in space. The proposed optimization algorithm, named SPORE, is characterized by a single particle which explores the parameter space according to an extremely simple self-adapting search logic. Thanks to its simplicity, SPORE is way faster than other methods previously proposed in the literature, being able to obtain sufficiently good results in a remarkably short computational time (on average, 2 ms, that is from two to three orders of magnitude smaller than other methods in the literature). Additionally, since our method employs a single particle at every step of the optimization process, its memory footprint is dramatically lower than, for example, population-based algorithms such as GA or PSO (as used in [4]), or other modern algorithmic structures employing covariance matrices or solution archives. Thus our method not only is suitable for fast real-time magnetic moment detection, but also allows for possible implementations on embedded systems endowed with limited CPU power and memory. This might be, for example, the case of portable biomedical detectors or portable magnetic scanners that could be used in structural non-invasive inspection.

To test the proposed approach, we built an experimental setup composed of three off-the-shelf 3-axis magnetic field sensors, and designed a Java Graphical User Interface (GUI) in which the position and orientation of the magnetic moment is displayed, in a 3-D environment, on the screen of a computer connected to the sensors via USB. An optimization process is performed in background every time a new set of sensor data (3 samples X–Y–Z, one per sensor) is available for fitting, and the GUI is updated in real-time while the magnetic moment moves around the sensors' detectable area. To asses the superiority of our method in terms of computational time and fitting error, we compared it with a selection of state-of-the-art real-parameter optimization algorithms, including recent variants of PSO and differential evolution (DE), as well as some modern single solution optimization algorithms and classic local search methods.

The remainder of this paper is organized as follows. The next section describes the physical model of a single dipole moment and how its inverse formulation can be interpreted as a real-parameter optimization problem. Section 'Experimental setup' describes the experimental setup used for tests, while in Section 'Single Particle Optimization with Restarted Exploration' we describe our new single particle optimization algorithm. Section 'Experimental Results' presents the experimental results obtained with SPORE in comparison with other real-parameter optimization algorithms. Finally, Section 'Conclusions and future works' gives the conclusion of this study and suggests a few possible industrial applications that might be investigated in the future.

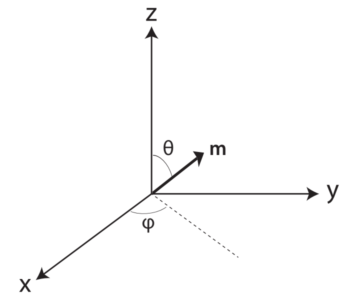

Fig. 1. The orientation of **m** is represented in spherical coordinates (M, θ, ϕ).

Background: magnetic dipole moment

In order to find the location, orientation and spatial structure of magnetic objects simply by measuring the magnetic fields they induce, one needs to be able to find the solution to an inverse problem. Although the magnetic field around a magnetic object can be calculated relatively easily, doing the inverse operation (i.e. finding its structure, position and orientation based on the magnetic field measurements) is generally more difficult, as it requires the use of an efficient fitting algorithm and often also a list of assumptions to limit the search space. Similarly to what was done for instance in [1] and [2], in this section we first formulate the direct expression of the external magnetic field induced by a single magnetic dipole moment, and then we define its inverse problem as an optimization problem.

Direct formulation

The external magnetic field $\mathbf{H}(\mathbf{r})$ induced by a single magnetic moment $\mathbf{m}$ is given by [14]:

$$\mathbf{H}(\mathbf{r}) = \frac{1}{4\pi||\mathbf{r}||^3}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{||\mathbf{r}||^2} - \mathbf{m}\right) \tag{1}$$

where $\mathbf{r}$ denotes the vector from the magnetic moment to the point in space where the field is calculated. Because the magnitude of the magnetic moment is usually fixed and for symmetry reasons, we choose for a representation of the moment orientation in spherical coordinates.

Fig. 1 shows the general convention we use for the coordinate system of $\mathbf{m}$. The angle θ represents the angle between the Z-axis and the XY-plane, whereas ϕ denotes the angle within the XY-plane. Hence, the orientation of $\mathbf{m}$ in Cartesian coordinates can be rewritten as:

$$\mathbf{m}(x, y, z) = \begin{pmatrix} M\sin(\theta)\cos(\phi) \\ M\sin(\theta)\sin(\phi) \\ M\cos(\theta) \end{pmatrix} \tag{2}$$

where $M = ||\mathbf{m}||$ is constant for a single dipole moment. The position of the magnetic moment is denoted by the vector $\mathbf{r}_m(x, y, z)$. The magnetic field present at the position of the sensors is then given by Eq. (1) for $\mathbf{r} = \mathbf{r}_s - \mathbf{r}_m$ where $\mathbf{r}_s(x, y, z)$ is the position of the magnetic field sensor.

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