## Mechatronics 21 (2011) 156-165

Contents lists available at ScienceDirect

## **Mechatronics**

journal homepage: www.elsevier.com/locate/mechatronics

# Two-DOF magnetic orientation sensor using distributed multipole models for spherical wheel motor

## Hungsun Son<sup>a,\*</sup>, Kok-Meng Lee<sup>b</sup>

<sup>a</sup> School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore <sup>b</sup> Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

#### ARTICLE INFO

Article history: Received 30 April 2009 Accepted 5 October 2010 Available online 3 November 2010

Keywords: Hall sensor Magnetic field Magnetic dipole Orientation Position Spherical wheel motor

## ABSTRACT

This paper presents a new method for measuring a two degree-of-freedom (DOF) orientation of a permanent magnet (PM) based system using magnetic field measurements. The method exploits distributed multipole (DMP) modeling method to accurately predict a magnetic field, and provides a rational basis to inversely solve for the orientation of the PM from measured data. The PM-based magnetic sensor along with the ability to characterize the magnetic field in real-time offers advantages in sensing and control such as contact-free measurements eliminating frictional wears commonly encountered in existing designs with a combination of single-axis encoders, and high-speed sampling rate thus offering a higher bandwidth than methods based on imaging sensors. This paper demonstrates the efficient method capable of measuring the orientation of the PM by implementing it on a spherical wheel motor (SWM), where the two-DOF orientation is measured. Sensor performance has been studied both analytically and experimentally to validate the DMP-based sensor model. The results can offer valuable insights for optimizing contact-free sensor designs.

© 2010 Elsevier Ltd. All rights reserved.

Mechatronics

## 1. Introduction

Many modern devices rely on a magnetic sensor to measure their orientation/position for accurate motion control since it offers a number of advantages including contactless, compact, robust and low cost. However, position/orientation measurements using the magnetic sensor have many difficulties in particular for multi-axis applications (such as machine tools, automation equipments, gyroscope, mobile vehicles and medical instruments) because they involve accurately estimating magnetic fields and solving the inverse model which seeks the solution from measured magnetic data analytically or numerically in real-time. To be effective, methods to solve the inverse model for magnetic sensors not only must be computationally efficient but also accurate; the problem remains a challenge to be solved.

Numerous techniques for orientation/position sensing have been widely developed using an excitation magnetic source such as a coil modeled as a dipole [1,2] where the principle of measurement is based on analyzing both phase lock loop and amplitude between originally excited and measured signals. In general, the phase-locking method provides good tracking accuracy but often requires additional devices including a power supply and electric wire connected to the coil. In addition, the magnetic field is relatively weak (mainly due to heat generation) as compared to that of a permanent magnet (PM) for the same volume. An effective alternative is the use of a PM as the source to provide a strong magnetic field without any power source and electric wire, which enables the system to be more compactly designed. Traditionally, constant-field magnetic sensors have been dominant in a singleaxis rotary machine [3,4] for position sensing but recently several studies involving three-dimensional position detection have been developed in diverse applications [5–9]. In [6], a linear algorithm has been proposed to trace the magnet position and orientation for medical applications. This research employs a number of three-axis magnetic sensors, and utilizes an optimized algorithm to detect the local magnetic field in real-time. In addition to the sensing method, a compact magnetic sensor has been developed in [7] to measure both a magnetic field and its spatial gradient tensor simultaneously, and to detect the orientation and position of the PM. As a practical application, a noncontact joystick with a PM and a hall sensor has been developed to measure its orientation in [10,11]. In most of these studies, a single dipole approximation (or an empirical formulation) is commonly used since it offers a simple closed-form solution to characterize the magnetic field for computing the position in three-dimensional space. While the single dipole has been widely used to analyze a magnetic field at a sufficiently large distance [12,13], it generally gives a poor approximation when the length-scale of the field is relatively small.

Recently, Lee and Son [14,15] developed a new modeling method (referred to here as distributed multipoles or DMP) to derive closed-form solutions for characterizing magnetic fields of a PM



<sup>\*</sup> Corresponding author. Tel.: +65 67905508; fax: +65 67924062. *E-mail address*: hsson@ntu.edu.sg (H. Son).

<sup>0957-4158/\$ -</sup> see front matter  $\odot$  2010 Elsevier Ltd. All rights reserved. doi:10.1016/j.mechatronics.2010.10.001