Control Engineering Practice 24 (2014) 120–128

Contents lists available at ScienceDirect

Control Engineering Practice

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

Control system design and input shape for orientation of spherical wheel motor

Hungsun Son [a,*], Kok-Meng Lee [b]

[a] School of Mechanical and Advanced Materials Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan 689-798, Republic of Korea
[b] Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

ARTICLE INFO

Article history:
Received 8 July 2011
Accepted 15 November 2013
Available online 22 December 2013

Keywords:
Open-loop control
Closed-loop control
Input shaping
Magnetic field
Magnetic dipole
Multi-DOF spherical motor actuator

ABSTRACT

This paper presents control system design of a multi degrees-of-freedom (DOF) spherical wheel motor (SWM) in a class of ball-joint-like direct drive actuators to control orientation of the shaft. Three controllers (model based open-loop (OL), two closed-loop (CL) controllers) based on a push-pull torque model have been developed from rotor dynamics and magnetic field model referred to here as Distributed Multipole (DMP) model which provides accurate torque computation. The model based OL controller along with three control input shapes has been examined for the inclination control. Their results offer physical intuition, practical effectiveness, and also demonstrate the accuracy of magnetic field and torque computation. Then, two feedback controllers, a PD controller with and without the observer, have been developed for regulating its rotor inclination and experimentally evaluated against the OL controller. Finally, the performance on each controller has been compared to show the effect of the controllers on transient response. The experimental results verify control system design and demonstrate the motion capability of the SWM. While the experimental results illustrate the ability to control, they also reveal constraints and limitations of the controllers and provide insights for future design of control systems for the SWM.

1. Introduction

Research in robotics and automation to replace human operations requiring highly dexterous but repetitive tasks has been persistent for several decades (Saito, Imaizumi, Ueno, & Higuchi, 2009; Tanaka et al., 2009; Mitsantisuk, Katsura, & Ohishi, 2010). Motion of humans is dexterous but generally poor in precision and speed in manipulation. In particular, jobs requiring repetitive motions in stressful environment have a potential to cause disorders in human joint, wrist and shoulder. These above reasons have motivated significant efforts to explore alternative designs of multi-DOF actuators capable of mimicking human motions. Existing single-axis machines (though can be quantitatively very precise yet fast and tireless) often achieve multi-DOF dexterity with external (serial or parallel) mechanisms at the expense of precision and speed. This paper presents a multi-axe spinner, referred to as a spherical wheel motor (SWM), an alternative direct-drive design built upon the concept of a ball-joint-like motor originally conceptualized in Lee and Kwan (1991).

An electromagnetic actuator utilizing both permanent magnets (PMs) and electromagnets (EMs) has been controlled by open-loop (OL) or closed-loop (CL) depending on design and operation principle. OL controls inherently have limited performances particularly when positioning in a 3-D space, but it helps understand the operational principle and is essential to design CL controllers, whereas the OL control still has difficulties due to a number of uncertainties involving system identification and force/torque computation (Yan, Chen, Yang, & Lee, 2006; Lee, Sosseh, & Wei, 2004; Xia, Li, & Shi, 2008; Yan et al., 2008; Lee, Bai, & Lim, 2009). Due to nonlinear rotor dynamics, complex magnetic fields and orientation measurement (Son & Lee, 2008), it is particularly difficult to design control systems for spherical motors.

Most existing spherical motors base operation on principles similar to their single-axis counterparts (Desai, Krishnamurthy, Schofield, & Emadi, 2010) (DC, switched-reluctance motors or PM stepper). Controller design techniques for the single-axis actuators can be readily extended to multi-DOF spherical actuators; among these are techniques (such as nonlinear observer, feedback linearization, adaptive and robust control, etc.) recently studied by numerous researchers. In particular, the nonlinear observer that estimates the transient state of a power system in Forrai, Ueda, and Yumura (2007) has been applied to a smooth-rotor synchronous generator. In Hajian, Soltani, Markadeh, and Hosseinnia (2010), an adaptive nonlinear direct-torque control (based on rotor flux and EM torque model) for induction motors is presented. Recently, high gain observers have played an important role in

* Corresponding author. Tel.: +82 52 2172343; fax: +82 52 2172408.
E-mail address: hson@unist.ac.kr (H. Son).

0967-0661/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conengprac.2013.11.013

design of output feedback control of nonlinear systems (Dabroom & Khalil, 2001; Zhu, Kaddouri, Dessaint, & Akhrif, 2001; Cirrincione, Pucci, Cirrincione, & Capolino, 2007; Li, 2009; Foo & Rahman, 2010). In Dabroom and Khalil (2001), a nonlinear digital control system using high-gain observers has been analyzed with experimental validation, and demonstrated that the sampled-data controller approaches the performance of a continuous time controller with sufficiently high sampling frequency and large observer gain. A nonlinear state observer was used to estimate the rotor position and speed for a linearization-based controller (Zhu et al., 2001) where the stability of the controller/observer for the closed-loop system was confirmed using Lyapunov stability theory. In Li (2009), a neural-network based robust controller to reduce the effects of uncertainties and disturbances on the tracking performance a spherical stepper motor in 3-D space has been developed; the trade-off is the need to train neurons to improve the performance before applied.

In this paper, design of control systems and various control input shapers for feed-forward and closed-loop control of a spherical motor have been experimentally investigated, which offers valuable insights for performance improvement and a basis for developing more advanced control systems. The remainder of this paper offers the following:

(1) First, the paper presents both mechanical and electrical structural features of a SWM designed for manipulating the inclination of a rotor. Both structures are symmetrically designed so that it can be controlled based on a push-pull principle.
(2) A model-based open-loop controller along with three input shapes; namely, step, input shaping and ramp, has been examined. Their results offer physical intuition of control, practical effectiveness, and demonstrate the accuracy of a magnetic field and torque model.
(3) Finally, two closed-loop controllers based on the OL controllers; PD with and without an observer, have been designed and implemented on a prototype SWM consisting of 20 stator electromagnets (EMs) and 16 rotor PMs. The experimental results verify the control system designs and offer intuitive insights into the effects of uncertainties on motion control.

2. Control system design of SWM

Fig. 1(a) shows the prototype SWM originally developed in Lee and Son (2007) along with the schematics in Fig. 1(b) illustrating its mechanical and electrical structure. The SWM shown in Fig. 1(a) consists of two-layers of equally-spaced 8 cylindrical PMs (m_r=16) embedded in the rotor supported through a universal ball bearing on the stator that houses two-layer of 10 equally-spaced EMs (m_s=20), the currents through which serve as controlling inputs to the SMW. The rotor (xyz coordinate frame) is concentric, and moves with respect to the stator (XYZ reference frame). The rotor PMs are arranged in pairs and every two pairs form a plane with their magnetization axes passing radially through the centre. The stator EMs (serially connected in pairs) follow similar arrangement as for the PMs; the PMs and EMs are symmetric electrically and mechanically with respect to xyz and XYZ frames shown in Fig. 1(b). Thus, a magnetic vector corresponding to each PM and EM can be expressed in (1) and (2), respectively.

$$\mathbf{r}_k = (-1)^{k-1}[\mathbf{T}][\ \cos\phi_r \cos\delta_{rk} \quad \cos\phi_r \sin\delta_{rk} \quad \sin\phi_r\ ]^T \tag{1}$$

where [**T**] is a coordinate transformation matrix of α, β, and γ; the subscript rk indicates the kth PM pair of the rotor;$\delta_{rk} = (k-1)\delta_r$; k=1, 2… m_r; and $\delta_r = 2\pi/m_r$.

$$\mathbf{s}_j = [\ \cos\phi_s \cos\delta_{sj} \quad \cos\phi_s \sin\delta_{sj} \quad \sin\phi_s\ ]^T \tag{2}$$

where the subscript sj denotes the jth EM pair of the stator; $\delta_{sj} = (j-1)\delta_s$; j=1, 2… m_s; and$\delta_s = 2\pi/m_s$.

The above symmetric arrangements enable the SWM to operate on a push-pull principle about a desired inclination by appropriately controlling current inputs to the EMs to generate a resultant pair of planar torques (with equal magnitude but opposite direction). Consequently, the differential current inputs create a driving torque $\mathbf{T}(=\mathbf{T}_+ + \mathbf{T}_-)$ and move the rotor to a desired equilibrium orientation, where **T** finally become and maintain at zero.

The SWM features its orientation control with/without continuously spinning of the rotor. Despite its simple structure in the design, there are a number of difficulties in analyzing magnetic field associated with dynamic motion for torque computation and controlling motion. However, the feasibility of an OL control for the SWM, which decouples the control of the rotor inclination (α and β) based on torque models from that of the switching spin rate ($\dot{\gamma}$), has been demonstrated in Son and Lee (2010). The independent control of the inclination and spin has been achieved by varying the input frequency for a spinning rate, and using only the magnitude of current inputs for controlling the rotor orientation. The control system performance, particularly during the transient, can be further improved by means of feedback control and/or feed-forward compensation with model-based input shapers.

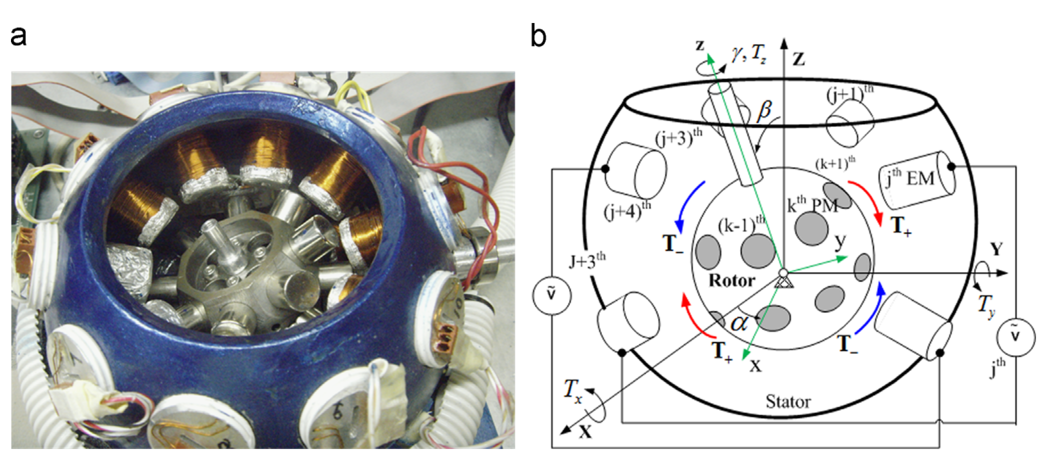

Fig. 1. Spherical wheel motor (SWM). (a) Prototype SWM, (b) Illustrative schematics.