Sensors and Actuators A 180 (2012) 75–86

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

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

Design and control of a three degree-of-freedom permanent magnet spherical actuator

Weihai Chen, Liang Zhang*, Liang Yan, Jingmeng Liu

School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 28 November 2011
Received in revised form 12 April 2012
Accepted 13 April 2012
Available online 21 April 2012

Keywords:
Spherical actuator
Orientation measurement
Torque modeling
Control algorithm

ABSTRACT

This paper presents a permanent magnet (PM) spherical actuator embedded with a novel three-dimensional (3D) orientation measurement system. The study covers actuator design, torque modeling, and motion control. The spherical actuator consists of a stator with 24 coils and a rotor with 8 PM poles. A high accuracy and resolution, non-blinding 3D measurement mechanism is designed for the rotor orientation detection. The torque output is formulated from finite element (FE) computation and curve fitting method. Due to the nonlinear property of dynamic model, computed torque control law is utilized for the three degree-of-freedom (3-DOF) system motion control. The space geometry method is employed to study the redundancy feature of current inputs, which offers the opportunity for control optimization to improve the power efficiency and the fault tolerance capability of the spherical actuator. Simulations and experiments are then conducted on the developed prototype to validate the design concept, mathematic models and control strategy.

1. Introduction

With the rapid advancement of the robotics, precision assembling, flexible manufacturing and automation technology, there is increasingly demand of multiple degree-of-freedom (DOF) actuation systems. Conventionally, multi-DOF motions are achieved by connecting a few single-axis actuators in serial or parallel, which inevitably cause problems such as bulky structure, large backlash, slow response, low positioning precision and lack of dexterity. Therefore, researchers have proposed the concept of spherical actuator that can realize multi-DOF rotations in a single joint. Due to the advantages of compact structure, direct drive, low inertia moment and rapid response, it has wide potential applications in vision systems, robotic joints, machining tools, positioning devices, and radar tracking.

The research work on multi-DOF actuators has been carried out for several decades. The first 2-DOF spherical actuator [1] was designed by Williams et al. in the 1950s. Since then, spherical actuators with various structures and operating principles have been developed [2–17]. Correspondingly, orientation measurement methods have been proposed to detect the rotor motion in 3D space. One typical example is to use the measuring mechanism consisting of three encoders, two circular sliding guides and one sliding block [7]. This method provides high-precision measurement results. However, the measurement structure produces two-thirds of the inertia moment of the entire system, which significantly decreases the system dynamic performance. Another way is to use Hall-effect sensors to measure the flux density at certain points around the rotor, and then compute its orientation [2,5,11]. But the measurement resolution is quite low, because the magnetic field of the moving body does not vary much at certain positions. The vision-based method is realized by a spherical shell surface marked with grid patterns mounted on the rotor shaft [16]. Its resolution is constrained by the density of grid pattern. Optical sensor is also employed by researchers for the rotor orientation measurement [17]. The measurement result is very sensitive to the gap size and the relative motion speed between the moving surface and the sensor trip. In short, 3D measurement is a key problem that affects the development of spherical actuators.

Therefore, the objective of this paper is to design a spherical actuator with a high performance orientation measurement system. The spherical actuator designed here consists of a rotor with eight PM poles and a stator with twenty-four air-core coils. The rotor is connected to the stator through a spherical joint that can measure the orientation of rotor in three directions. Compared with other orientation measurement method, the proposed orientation measurement method can achieve high accuracy, rapid response, non-blinding area, and low extra inertia moment. Besides the measurement system, another contribution of this paper is the redundancy property of the spherical actuator is studied. One

* Corresponding author at: School of Automation Science and Electrical Engineering, Beihang University, XueYuan Road No. 37, HaiDian District, Beijing, China. Tel.: +86 10 8231 5560; fax: +86 10 8231 5920.
E-mail address: zlbuaa87@gmail.com (L. Zhang).

0924-4247/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2012.04.010

Table 1
Structure specifications.

Inner/outer stator radius	100/117 mm
Rotor radius	56.5 mm
Thickness of rotor shell	4 mm
Number of PM poles	8
Cylindrical PM	r = 10 mm, l = 20 mm
Number of coils	24/2 layers
Number of coil turns	1600
Maximum tilting angle	±15°

common feature of the existing electromagnetic spherical actuators is that the number of current inputs is more than that of torque output. This redundancy property has been studied by Wang et al. [11], and Lee et al. [7,9] to minimize the power consumption of spherical actuators. However, other benefits of redundancy such as fault tolerance have never been studied. It is one of the topics in this research paper.

The rest of the paper is organized as follows. Section 2 presents the design and prototyping of our spherical actuator. Section 3 formulates the analytical model of the torque output with curve fitting method. Section 4 presents the dynamic model of the rotor from Lagrange's equations. Section 5 introduces the control algorithm, and the redundancy property is studied. Section 6 illustrates the simulation results, and Section 7 presents the experiments. Finally, the paper is concluded in Section 8.

2. Design of the spherical actuator

2.1. Construction

The mechanical structure of the research prototype is shown in Fig. 1. It consists of a rotor and a shell-shaped stator. This rotor can generate continuous spinning motion about its output shaft, and incline about its equatorial plane to a position that the axes of a PM pole and the coil are aligned. The maximum tilting angle is ±15°. It can be increased up to about ±45° by incorporating more layers of coils.

The specification of the spherical actuator is listed in Table 1. The stator is made of aluminum due to its low cost and eases of fabrication. The space between the rotor and the stator facilitates the thermal dissipation. There are 24 holes on the stator shell symmetrically arranged about the stator equatorial plane in two layers. Air-core coils are mounted in these holes and point to the center of the stator. The axes of these holes pass through the stator center, and the outer part of these holes is threaded for the adjustment of the air gap. The absence of ferromagnetic material in the coil results in a linear correlation between the input currents and the output torque.

The inner structure of the rotor is shown in Fig. 2. The rotor shell is made of aluminum, as it has no influence on the magnetic field and reduces the inertia moment of the rotor. Rare earth NdFeB-N35UH is chosen as the PM poles material, since it has high coercive force. The rotor PM poles are arranged in an alternative polarization pattern that can achieve larger torque compared with the pattern with same polarization. Fig. 3 shows the distribution of the magnetic flux density vector produced by the rotor PM poles.

The magnetization axis of PM poles in the rotor frame are given by the unit vector of

$$\mathbf{r}_i = (-1)^{i-1}\left[\cos\left[\frac{\pi}{4}(i-1)\right] \quad \sin\left[\frac{\pi}{4}(i-1)\right] \quad 0\right]^T, \quad i = 1, \ldots, 8. \tag{1}$$

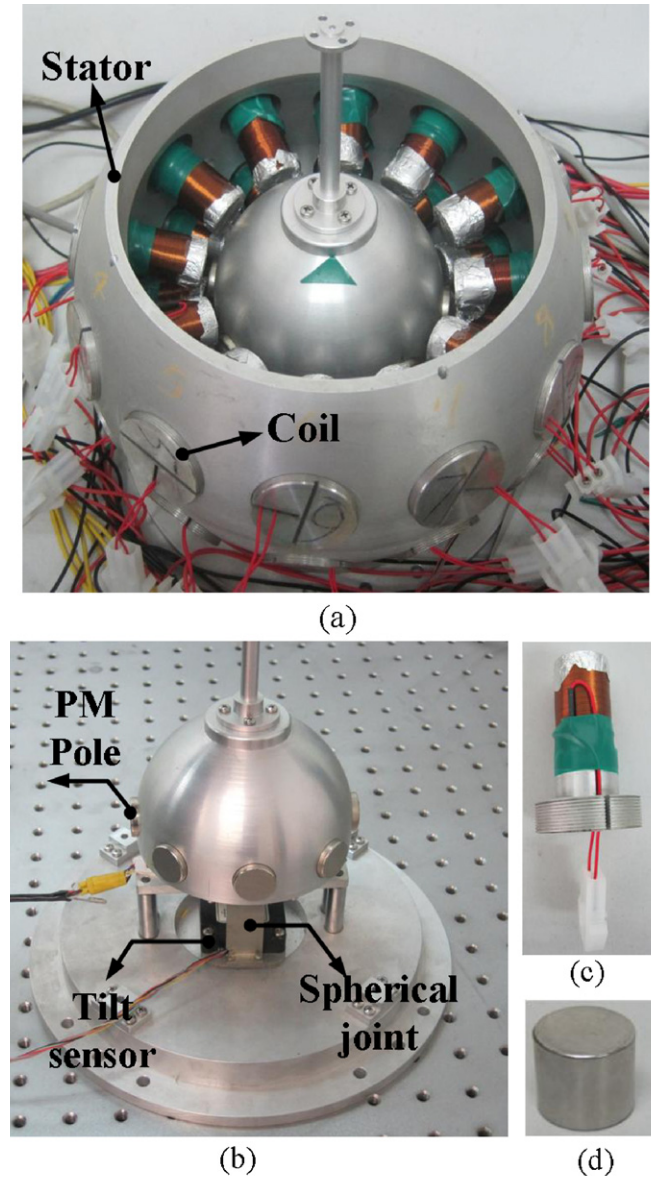

Fig. 1. Prototype of the spherical actuator: (a) stator, (b) rotor, (c) coil and (d) PM pole.

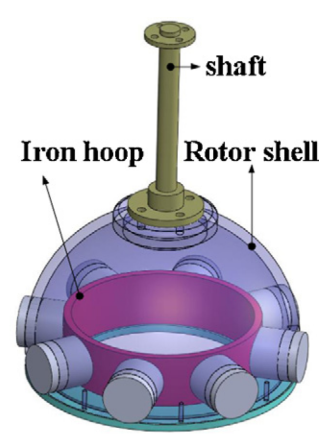

Fig. 2. Rotor structure.