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Hybrid torque modeling of spherical actuators with cylindrical-shaped magnet poles

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ABSTRACT

A ball-joint-like three-degree-of-freedom (3-DOF) spherical actuator which features a ball-shaped rotor with multiple permanent magnet (PM) poles and a spherical-shell-like stator with air-core coils is proposed to achieve omni-directional smooth motion in only one joint. Unlike previous study in which dihedral-shaped PMs are employed as the rotor poles, this paper utilizes cylindrical-shaped PMs to facilitate the fabrication and reduce the system cost significantly. Torque output of the spherical actuator is formulated with a hybrid method, i.e., using both analytical and experimental methodologies. Specifically, the analytical torque model of spherical actuator with dihedral-shaped PM poles is derived. Then a research prototype with cylindrical-shaped PM poles is developed, and a torque measurement testbed is built up to conduct experiment on the prototype. As the torque variation trend of actuators using two different types of PM poles with respect to the rotor orientation is similar, parameters in the analytical model are adjusted to fit with the experimental measurements. The resulting torque model can be employed for real-time motion control of the actuator. The cylindrical-shaped PM poles also reduce the inertial moment of the rotor by 60%, which is favorable for achieving better dynamic performance of the spherical actuator.

1. Introduction

Single-axis actuators based on various principles [1–4] have been developed for long history. Several single-axis actuators can be connected in parallel or in series to achieve multi-degree-of-freedom (multi-DOF) rotational motions. This type of mechanism has disadvantages of bulky structure, large inertia moment and singularity existence in workspace. To eliminate these drawbacks, spherical actuators that can generate multi-DOF rotational motion in only one joint have been proposed by researchers. The first 2-DOF spherical induction motor has been designed by Laithwaite and Williams [5,6]. Torque model of this induction motor was derived by integrating the Maxwell stress moment over the spherical rotor surface [7]. A spherical stepper [8,9] and a spherical wheel motor [10–12] have been developed by Lee et al. based on the principle of variable reluctance (VR). The torque output of these motors was formulated by using co-energy method, which shows that the actuator torque depends on the current inputs and the magnetic reluctance at air gaps [13]. Spherical actuators that can achieve 2/3-DOF motions have been developed by Wang et al. [14–16]. The torque output was formulated with Lorentz force law analytically. Chirikjian et al. [17] made a spherical stepper with a PM-pole rotor and a stator with an array of coils. Difference in the symmetric layout of rotor and stator poles allows stepping motion in three orientations. Yang et al. [18] have proposed a 3-DOF spherical actuator in which the rotor can make an arbitrary orientation and a spin by interactions among rotor and stator poles. The torque output was formulated with Coulomb's law. Kahlen et al. [19] have developed a spherical motor consisting of a rotor with 112 PM poles and a stator with 96 windings. The poles were arranged symmetrically corresponding to longitude and latitude of a globe. The torque was calculated numerically. Dehez et al. [20] developed a 2-DOF spherical induction motor with various rotor and stator structures. Its performance in terms of characteristic torque-speed and efficiency has been analyzed with Maxwell tensor.

In our previous study [21], a 3-DOF spherical actuator consisting of a PM-pole rotor and a stator with two layers of coils has been developed. The rotor and stator are parameterized, and generic method based on Lorentz force law was employed to formulate torque output of the actuator analytically. The proposed structure configuration allows more rotor and stator poles to be incorporated and thus to increase the working range as well as motion resolution of the actuator. However, the use of dihedral-shaped PM poles complicates the magnet fabrication and increases the system cost greatly. Therefore, in this study, cylindrical-shaped

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