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Prototype design of a multi-degree-of-freedom spherical permanent magnet gravity compensator

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Abstract
An innovative spherical actuator with integrated magnetic spherical gravity compensator is developed. Because of the patented magnetic spherical gravity compensator a higher torque density and a low energy consumption is achieved. Especially in mobile robotics applications such as, arm support systems, this is necessary to satisfy all requirements. To prove the working principle of this compensator a scaled prototype design is created. For this design the manufacturing limits are discussed and the resulting torque performance is obtained.

Keywords: Electromagnetic measurements, Electromagnetic modelling, Magnetic analysis, Magnetization, Magnetic field measurement, Magneto statics, Magnetic flux density, Permanent magnets

1. Introduction

The usage of robotics is rapidly growing in several fields such as, medical, industrial [2] and, assistive [3]. These robots mimic a ball and socket joint with several single-degree-of-freedom actuators. This results in large and cumbersome constructions with predefined sequences of rotation axes. To avoid such constructions a spherical actuator can be used [4]. This actuator provides the required degrees-of-freedom in a single actuator and has a free sequence of rotation axes. However, this actuator topology cannot achieve the required torque density without increasing the volume or complexity [4, 5]. Hence, none of any existing spherical actuator designs are suitable for mobile robotic applications.

By integrating a patented [1] spherical magnetic gravity compensator into a spherical actuator, compact and flexible robotic joint constructions can be created and all the requirements can be achieved by a single actuator. With the innovative spherical gravity compensator [6], the energy consumption is limited to a minimum and it has a low thermal gradient. Especially for mobile robotic applications such as arm support systems this new actuator topology is an excellent solution.

In this paper, a prototype design to prove the working principle of the spherical gravity compensator is created. The manufacturing limitations are investigated and their influences on the torque performance of the spherical gravity compensator are calculated. Due to these limitations a scaled prototype is created instead of the optimized design presented in [6].

2. Spherical gravity compensator design realization

The gravity compensator consists out of two concentric hemispherical permanent magnets as illustrated in figure 1a. These magnets have a radial and a parallel magnetization for the outer and inner permanent magnet as indicated in figure 1b. To compensate for the mass of a human arm during the movement as shown in figure 2, the gravity compensator generates a sinusoidal torque characteristic for the motion in the θ-direction. At the position θ =0 degrees there is no torque needed, whereas, at the position θ =90 degrees a maximum torque is required.

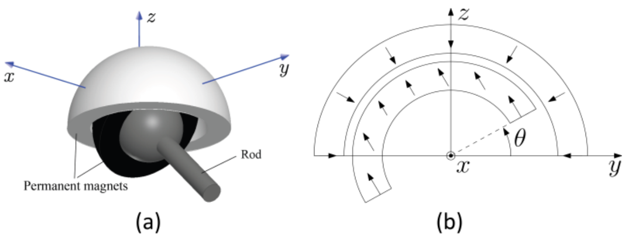

Figure 1. (a) Proposed magnetic based spherical gravity compensator (b) magnetization configuration of the hemispherical permanent magnets.

For the application of an arm support system, a sinusoidal torque characteristic is necessary with an amplitude of 12 Nm [5]. For the prototype, only commercially available component are used. This resulted in an inner spherical permanent magnet with a radius of 25.4 mm instead of 36 mm [6]. The parallel magnetized hemispherical permanent magnet is created out of a full spherical NdFeB magnet and wire eroded in half, as shown in Fig. 2a. For this prototype a solid hemispherical permanent magnet is considered instead of a hollow hemispherical permanent magnet, as show in figure 1b. A solid hemisphere generates 21 % more torque, as there is 32 % more magnetic material. However, due to the smaller radius the torque performance decreases with 30 % to 8 Nm. The geometric parameter and material properties are given in Table 1.

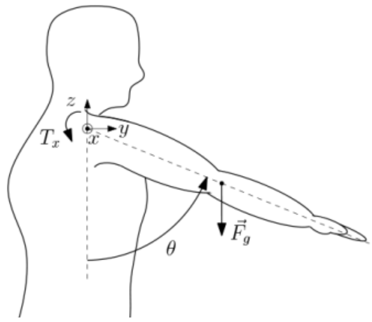

Figure 2. Schematic representation of a human upper limb to indicate the movement with respect to the gravity force.

The radial magnetization of the outer hemispherical permanent magnet is achieved by segmenting parallel magnetized cylindrical permanent magnets. Placing these magnets in a supporting structure, as shown in figure 3b, results in figure 3c. The geometric parameters and material properties of the inner and outer hemispherical permanent magnet, including the cylindrical magnets, are summarized in Table 1 and Table 2, respectively.

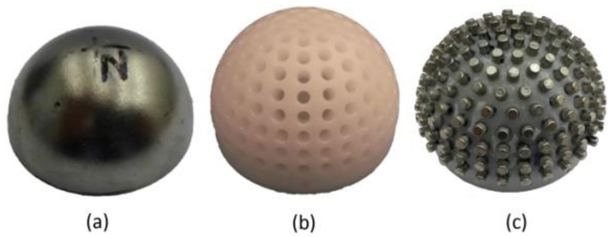

Figure 3. Realized (a) solid hemispherical permanent magnet with an axial magnetization (b) holder for the cylindrical permanent magnets (c) segmented outer spherical permanent magnet with approximated radial magnetization.

Table 1 Geometry parameters of the parallel magnetized inner hemispherical permanent magnet.

Parameter	Value	Description
R_h	25.4/mm	Hemipshere radius
B_{rem}	1.28/T	Remanent magnetic flux density

Table 2 Geometry parameters of the outer hemispherical permanent magnet and used cylindrical permanent magnets for the segmentation.

Parameter	Value	Description
R_{in}	27.9/mm	Inner hemisphere radius
R_{out}	40.4/mm	Outer hemisphere radius
Airgap	2.5/mm	Airgap lenght
R_c	4/mm	Diameter of cylinders
h	12.5/mm	Heigth of cylinders
B_{rem}	1.28/T	Remanent magnetic flux density
N	178	Number of magnets used

3. Torque comparison

The torque and force performance of the prototype design are shown in figure 4a and figure 4b, respectively. These results are obtained with 3D finite element analysis. Because of the symmetry, only the torque performance rotating about the *y*-axis is presented. As the design shows a sinusoidal torque characteristic it can be concluded that the approximated radial magnetic field satisfies the requirements. With the segmentation there is 68 % less magnetic material, this causes a torque performance decrease of 67 % compared to a full radial magnetized hemispherical permanent magnet.

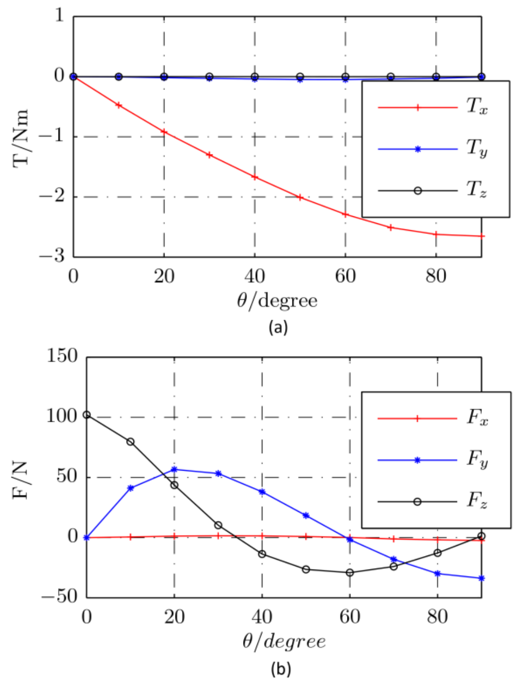

Figure 4. Torque performance of the radial magnetized (a) solid hemispherical permanent magnet (b) segmented hemispherical permanent magnet.

4. Conclusions

A scaled prototype design of a spherical permanent magnet gravity compensator has been created. Due to the scaling, the torque performance decreased with 33 %. The radial magnetization is approximated with a segmentation of 178 parallel magnetized cylindrical permanent magnets. This segmentation has no influence on the torque characteristic, only on the amplitude. A decrease in torque performance, caused by the segmentation is 67 % as there is 68 % less magnetic material. From all manufacturing limitations, the segmentation causes the larges decrease in torque performance.

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