A NEW TOPOLOGY OF A SPHERICAL ACTUATOR

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***Abstract* –This paper presents a new topology of an actuator which allows the precise control of the angular position. The proposed system is known as 3-DOF (Three Degrees of Freedom) Spherical Actuator. This actuator can be applied to a robotic eye or joints, as it has 3-DOF in a single block. Such spherical actuator is different among others publications, since it has only three coils, which simplify its construction. The actuator work s injecting different currents values (i_1, i_2, i_3) in each coil, then the generated resultant magnetic field can be positioned at any point of a hemisphere by controlling the currents intensities. The rotor is a spherical shell with a NdFeB permanent magnet inside it. The rotor magnet attempts to align with the resultant magnetic field which was produced by the coils and then rotating movement can be carried out just changing the drive sequence of the coils. Moreover, one mini-camera is attached at the spherical shell to emulate the human eye movement. As result, this paper deals with the design of a spherical actuator with a reduced number of coils, which can be positioned everywhere at the top of a hemisphere.**

***Keywords*– Spherical actuator, permanent magnet, 3-DOF.**

NOMENCLATURE

B_1,B_2,B_3	Coil 1, Coil 2 and Coil 3.
i_1, i_2, i_3	Current value of B_1, B_2, B_3
NdFeB	Neodymium-Iron-Boron
3-DOF	Three Degrees of Freedom.
PWM	Pulse Width Modulation.
SWM	Spherical Wheel Motor.

I. INTRODUCTION

Nowadays, the increasing numbers of new technologies which require complex motions have been developed. In this way, new types of actuators are required for precise control of the angular or linear position [1], [2]. In order to achieve these movements, usually either the linear or the rotary servo motors are used, as shown in Figure 1 (stepper motors + transmission gears) [3].

The linear and rotary topologies have only one degree of freedom, and they allow only the linear or angular movement. Some actuators of multiple degrees of freedom have been required, and it is an emerging trends of the machine design and manufacturing equipment, as they can perform their movements in different ways with high precision and without a complex mechanical systems necessary to processes the movements, i.e. rotary ↔ linear. Moreover, these new actuators are simple, compact and robust [2], [3].

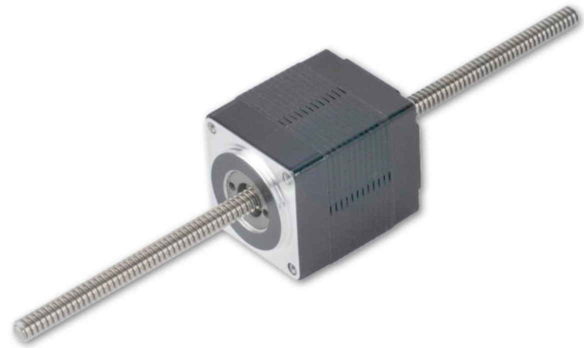

Fig. 1. Linear actuator stepper motor.

Usually, one application with multiple degrees of freedom is implemented by one motor in each axis to execute the movement. This results in a complex mechanical transmission system to the load, which can cause positioning errors due to the backlash and mechanical deformations of the gears. Moreover, these 3-DOF systems are massive due to the several actuators and gearboxes. [4] [5].

Therefore, the development of a 3-DOF actuator in a single piece, being lightweight, robust and having few moving parts with easy control, is expected for several applications in the robotics and manufacture industry [2], [5], [6], [7].

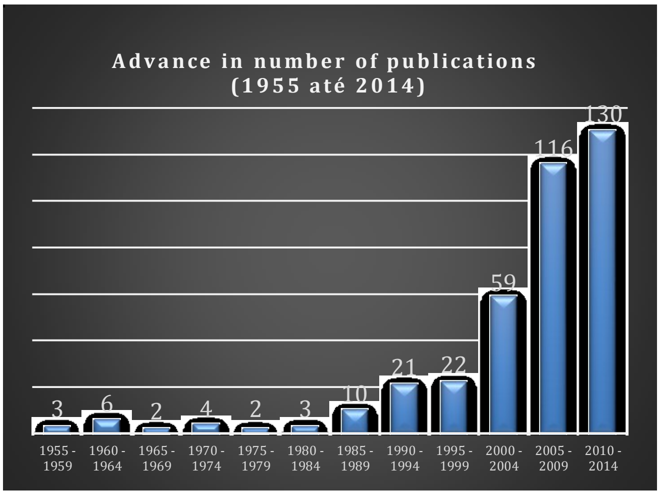

Fig. 2. Number of publications over the past decades with terms: Spherical Motor or Spherical Actuators.

The number of publications on the subject of spherical motor or spherical actuators is growing every year. Figure 2 shows the relationship between the numbers of published papers over the past few years [8].

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A. Multi-degree-of-freedom (MDOF) actuator

When we deal with movement in robotics, it is impossible not to talk about eletric motors, which is the main element to produce motion. Then, each day several efforts are used looking the development of new solutions to produce motion for a plenty of applications. The reader can imagine an exoskeleton with actuator that replaces a joint, or an actuator similar to a human eye that revolves around its own axis.

Devices with multiple degrees of freedom (MDOF) have been suggested in several others publications [2], [5], [9], [10]. The proposed actuator is a device that can rotate around its origin because it has a spherical rotor. Furthermore, it can be applied in video surveillance camera systems, to emulate a robotic eye and as joint prosthesis for knee, wrist, hip or shoulder. The referred spherical movement is a 3-DOF motion which is described along a spherical surface with the origin at the middle of a fixed body, as illustrated in Figure 2 [6].

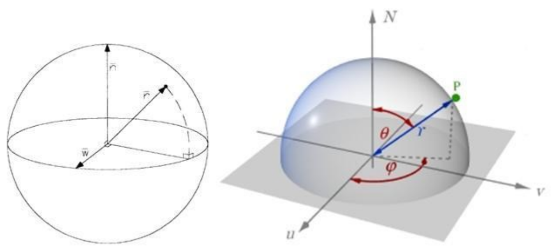
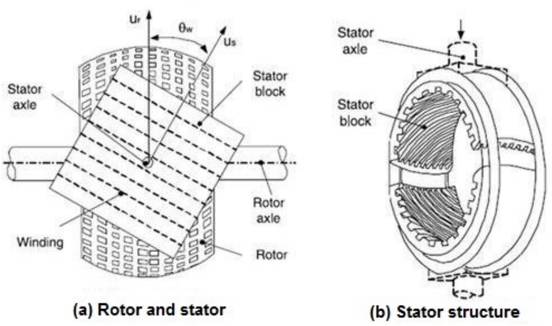


Fig. 2. Spherical surface with the origin at the middle (point O)

B. Firsts published works with the spherical actuator

In the literature, the spherical actuators designs are based on the pure electromagnetic calculations. One early work is from Williams and Laithwaite et al. [10], they designed the first induction motor with a spherical actuation, where the rotor is made of a ferromagnetic material with a barrel shaped spherical surface, as shown in Figure 3 (a). The stator consists of two windings, (see Figure 3 (b)), which can be twisted with an angle θ around an axis perpendicular to the



rotor axis.

Fig. 3. Spherical Induction Motor Acting (Rotor / Stator). [10]

Different models are proposed after the latter described publication. Thereby, an interesting model is the spherical motor (SWM - Spherical Wheel Motor), proposed by Lee et al. The 3-DOF actuator is similar to a stepper motor, and angular movement is reached by an open-loop control. It proposes different sequences to drive the stator coils to produce a fractional or a full step, by specifying for which pole the current value should be controlled. This actuator has ten coils on the stator, as shown in Figure 4, and the rotor consists of several permanent magnets (PM) [2], [11].

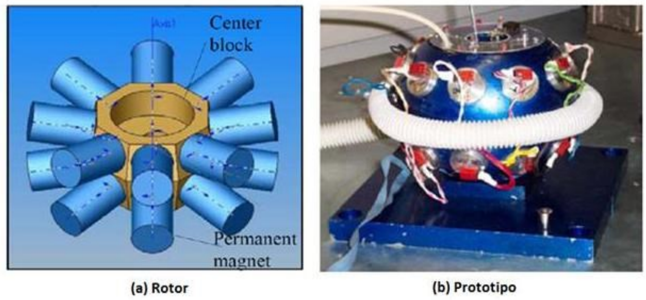


Fig. 4. 3-DOF Spherical Motor proposed by Lee et al. [11]

II. PROPOSED SPHERICAL ACTUATOR MODEL

This paper deals with the design of a spherical actuator with a reduced number of coils, which can be positioned everywhere at the top of a hemisphere. The rotor is a spherical shell with a NdFeB PM inside it. The rotor magnet attempts to align with the resultant magnetic field which was produced by the coils and then rotating movement can be carried out just changing the drive sequence of the coils (B_1, B_2, B_3). Figure 5 shows the designed coils. The coils are geometrically spaced by 120 degrees from each other and 90 degrees to the origin (vertical Z axis of the system).

A. Coil design

Three coils should be produced with the same characteristics (inductance, size, material), as they should generate the same magnetic field intensity for the same applied current value. In this prototype, the coils were designed for the maximum current of 3 amperes. Figure 5 shows the designed coil.

Fig. 5. Designed coils used to produce one magnetic field component of the spherical actuator.

The coil core is made of a ferrite rod IP6 type, which has the BH curve illustrated in Figure 6. During the experimental tests, the coil reached an average temperature of 76 ° C for the maximum current value (3A).

B. Spherical Actuator design

The stator of the spherical actuators has three coil windings displaced at 120° from each other, which a DC-current will be injected to produce a resultant main magnetic field. For each current value injected into a single coil, one resultant magnetic field is produced, thus we can control the spatial direction of this main field. The spherical rotor consists of a free movable spherical shell having a PM inside it. The PM will align with the main resulting magnetic field generated by the stator coils. Therefore, the actuator stick can be oriented at any spatial position, by controlling the current values in each stator coil winding. For a simple changing of the coil driving sequence, the stick has a new position.

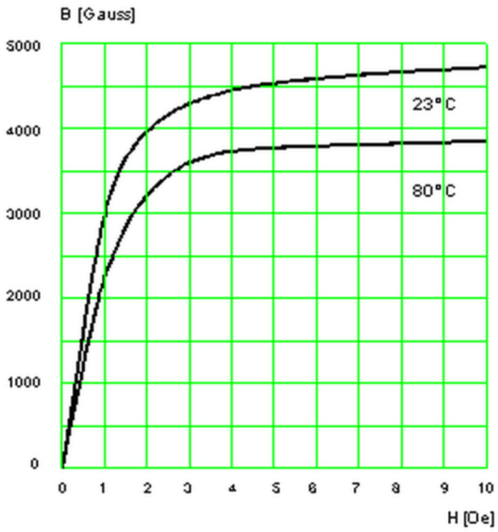


Fig. 6. Core BH curve for the IP6 material. [12].

Figure 7 shows the designed prototype of the proposed spherical actuator. It is essential to have a perfect symmetry in the designed spherical motor to ensure that the generated main field can be located anywhere at the hemisphere.

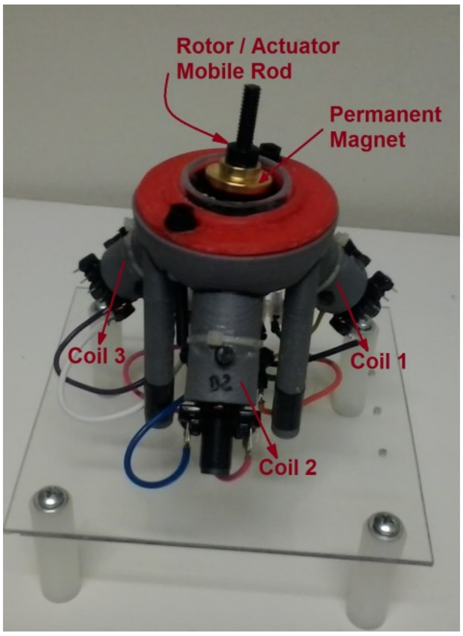


Fig. 7. Designed spherical actuator.

C. Spherical motor controller

The current control is performed by a microcontroller which receives the current references from a personal computer (PC) via Matlab®. The microcontroller is responsible to deliver the gating signals (Pulse Width Modulation) to each driver, where the coils windings are connected, as shown in Figure 8. Therefore, the spherical motor controller is composed by a H-bridge power drive and a microcontroller control board.

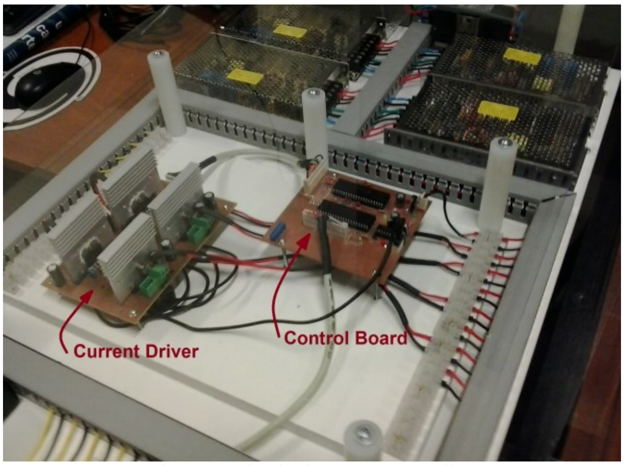


Fig. 8. Spherical motor controller.

III. SPHERICAL ACTUATOR WORKING PRINCIPLE

The spherical actuator should be positioned at a point (P) of a spherical shell, as depicted in Figure 9. Regarding the location of the coil windings, the rotor stick can be positioned only in the top hemisphere of the sphere surface. Therefore, it is similar to the covered area achieved by a human eye.

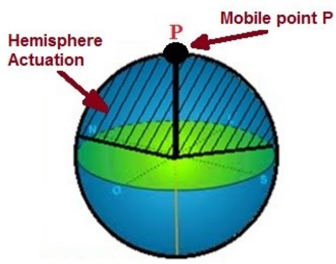


Fig. 9. Proposed spherical actuator.

The coils are geometrically spaced by 120 degrees from each other and 90 degrees spaced to the origin. The resulting main magnetic field is given by the sum of each magnetic field vector produced by coil. As result, the control of the current intensities can perform the actual location of the rotor stick, since the PM inside the rotor shell tries to align itself with the main magnetic field.

The produced magnetic **H** field at the point P (see Fig 9) is given by the length L, the radius R, the number of turn N of the coil and the injected current I, as described by the equation 1.

$$d\vec{H} = \frac{I.R^2.{}^{N}/_{L}\,dz}{2.(R^2+z^2)^{3/2}} \tag{1}$$

Supposing that each coil generates a field component a, b, c, then, the coil B1 has the components (a_1, b_1, c_1), the coil B_2 has the components (a_2, b_2, c_2) and the coil B_3 has the components (a_3, b_3, c_3), where each resultant component is described by Equation 2.

$$
\begin{aligned}
Z_1 &= (a_1) + (a_2) + (a_3) \\
Z_2 &= (b_1) + (b_2) + (b_3) \\
Z_3 &= (c_1) + (c_2) + (c_3)
\end{aligned} \tag{2}
$$

Furthermore, the component for each axis in Cartesian coordinates is given by equation 3.

$$
P\,(x, y, z) = (\,Z_1,\, Z_2,\, Z_3) \tag{3}
$$

Transforming the point P of Figure 10 to spherical coordinates, we can determine the equations 4.

$$
\begin{aligned}
r &= \sqrt{Z_1^2 + Z_2^2 + Z_3^2} \\
\emptyset &= arctan\frac{Z_2}{Z_1} \\
\theta &= arctan\frac{\sqrt{Z_1^2 + Z_2^2}}{Z_3}
\end{aligned} \tag{4}
$$

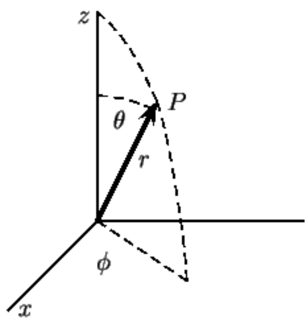


Fig. 9. Location of the Point (P) in the hemisphere.

IV. CONCLUSIONS

In the described and implemented prototype, we can control the actual position of the rotor stick by calculating the direction of the resultant magnetic-field H, through the currents (i1, i2, i3) applied to each coil (B_1, B_2, B_3). The experimental test has shown that the rotor stick remains always at the chosen point P, just controlling the current values. Moreover, it shows that the proposed topology is valid to act as a spherical actuator and it has 3-DOF.

One possible application of the spherical actuator is for a robotic vision system which emulates the human eye movement. The next step of this work is to close the position loop control, in order to avoid an external disturbance. Furthermore, the mathematical model of the proposed spherical model should be determined. At last, the main idea behind this paper is to present a simple actuator, which uses only three coils to control the actuator position.

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