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A Novel Approach In Generating 3-DOF Motions

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Abstract **- Primary objective in the design of spherical actuators or motors is to achieve 3-DOF motions within a compact structure. In the realization of this desired motion, various actuating methodologies have been proposed. In the process of achieving a true 3-DOF motions, spin of the rotor has always been a hurdle for many designers. In this paper, a new and innovative actuating principle coined as the Progressive Wave Method is being proposed and discussed. The novelty lies in the technique to creating the pan, tilt and spin motion. This approach allows pan and tilt motion to be decoupled from the spin motion and thus achieving 3-DOF motions within a single system. A prototype was developed and the proposed working principle was validated.**

Index Terms - 3-DOF motions, progressive wave method, pan, tilt and spin.

I. INTRODUCTION

The proliferation of technology has opened the door to an ever-increasing spectrum of application in the robotics sectors. The advancement of robotics manipulator has motivated the development of multi-DOF motors and actuators. Therefore a system with multi-DOF of controller motion is extremely desirable. The history of spherical actuator, or motor, dates back to the mid-1950s. The first spherical induction motor was designed and constructed by Williams and Laithwaite *et al*. [1-3] from the University of Manchester. Precise manipulation task requires small, high bandwidth motions where small weight-to-force ratios and innovative end effectors offers. In view of this, Vachtsevanos *et al*. invented a new robotic manipulator incorporating a novel spherical motor in a single [4,5]. Hollis *et al*. carried out concurrent work with the same objective of improving existing robotics systems. The proposed design was a direct current device with 6-DOF named the “Magic Wrist” [6-8].

From France, Foggia *et al*. presented yet another design of an electromagnetic actuator rotating around three independent axes [9]. Kaneko *et al*. developed a spherical DC motor with 3-DOF motions [10]. In the U.S., Lee *et al*. was involved in the research work of spherical in-parallel actuators [11-13]. Another research project "Kugelmotor" was financially supported by the Volkswagenstiftung and undertaken by a joint effort of three institutes of Aachen University of Technology, Germany [14]. Chirikjian *et al*. from Johns Hopkins University offered a spherical stepper motor. The prototype as described was able to achieve a much wider range from the mechanical design of stator by not enveloping the rotor [15]. From the United Kingdom, Wang *et al*. developed another spherical permanent magnet motor [16-18]. Recently, a joint effort between SIMTech (Singapore Institute of Manufacturing Technology), Nanyang Technological University and Georgia Institute of Technology conceived yet another spherical actuator for high precision application [19-21].

From the above concise review into the research and development of multi-DOF actuators, one can concur on the industry’s need for multi-DOF motion within a compact joint or structure. By encompassing multi-DOF motion excluding the presence of auxiliary systems not only enhances the system dynamic response but also improves structural rigidity and avoid workspace singularities.

II. OBJECTIVES

Prior to the discussion of the proposed actuating approach, let us define the terms used in this paper for the description of 3-DOF motions. Fig. 1 depicts a typical rotor with an output shaft. From the reference coordinate system as shown, we define pan and tilt as the rotational motion about the respective X and Y-axes. Correspondingly, spin is defined as the rotation about the Z-axis.

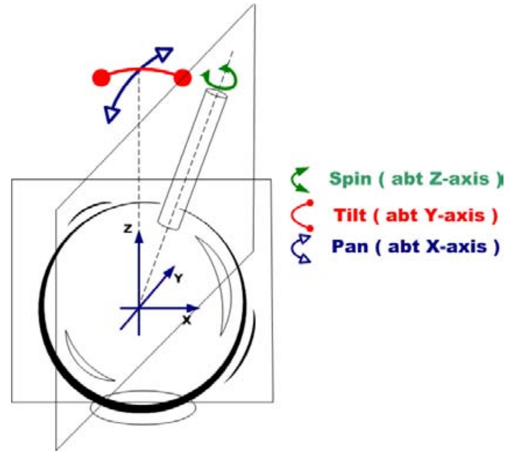

Fig. 1 Definition of pan, tilt and spin.

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As reviewed in the preceding section, the shortfall of practically all spherical actuator design is the realization of decoupled pan and tilt motion with the spin motion. In most design, these three motions are coupled and actuated simultaneously to achieve 3-DOF movements. Thus, to maneuver the rotor to a desired orientation before spinning occurs remains a hurdle to be overcome.

Another redundant feature observed from some existing spherical actuators design is the workspace of the rotor. Without doubt, the intention of a spherical actuator is to achieve 3-DOF motions within a compact structure or joint. But that does not imply that the workspace of the rotor or output shaft is desired to cover the entire spherical spectrum. In fact, the required workspace of a practical spherical actuator is always constrained by its application and support mechanism design. In any case, the utilization of the full spherical surface will never occur due to the inevitable presence of output and support mechanism.

Keeping these design objectives in mind, an efficient multi-DOF actuator is one that is structurally rigid so as to accomplish rapid, continuous and isotropic resolution in all directions and also possesses no singularity within workspace except the boundary. In this paper, a novel actuating method is being proposed in view of achieving decoupled 3-DOF motions. The structure of this spherical actuator is simple and actuating components are kept at the minimum.

III. METHODOLOGY

Existing prototypes creates spin either by simultaneous actuation or through commutations means. By energizing the stator poles sequentially, the rotor poles will be attracted to the corresponding stator poles and thus achieving the rotational motion. The shortfall of this technique is more prominent when the angular velocity is required is higher. At higher velocity, "slip" will occur between the rotor and commutation of the stator poles. The primary rationale for this trend is due to the induction time required between the magnetic fields. Furthermore, the absence of non-ferrous material within stator coils will contribute to this delay, as forces produced are considerably lower than ferrous core pole.

Putting things into perspective, the utilization of air core coils can eliminate the presence of detent force, eddy current and avoid non-linearity within the system. On the other hand, the employment of rare earth magnets as the rotor poles was to exploit the high magnetic field strength these materials yield. Thus, it would be ideal if we were able to generate rotation by capitalizing on the strength and linearity of the current mentioned system. The key factor for the slip and inefficiency lies in the commutation between the respective poles. Therefore, we propose an actuation scheme in which, is continuous in nature rather than pulsating.

A. Proposed actuating method

As we are well aware, magnetic fields are being formed round the vicinity of magnets or current carrying conductors. These fields are basically 3-D in nature. If we picture these magnetic fields on a plane, having adjacent magnets placed along side with each other, they fashioned themselves as a surface having an undulating profile as illustrated in Fig. 2(a).

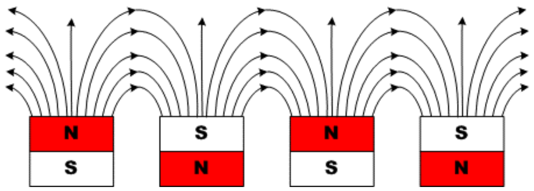

Fig. 2(a) Magnetic field of adjacent magnets.

Extending this phenomenon, we can imagine the undulating profile analogous to a mechanical gear as shown in Fig. 2(b).

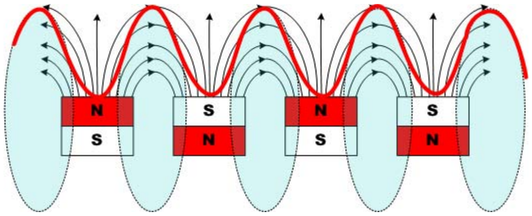

Fig. 2(b) "Virtual gear" created by magnetic fields.

The above-mentioned proposition of the magnetic field distribution was further attest by the 2-D FEM analysis shown in Fig. 2(c).

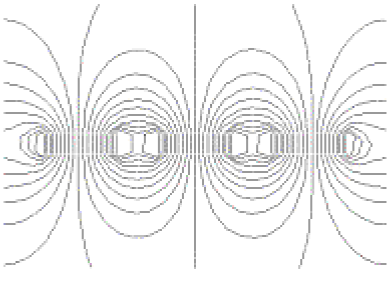

Fig. 2(c) Verification of magnetic flux distribution of a N-S-N configuration.

Continuous motion of the rotor can be conceived if we envision the rotor being a "virtual gear" formed by the magnetic field of the rotor poles permanent magnets. By coupling this to the stator virtual gear, in this case, created by energizing the stator coils, we are able to generate rotational motion as shown in Fig. 3(a) below.

This proposed actuation method could be associated with the same way worm gears are being turned as reflected in Fig. 3(b).

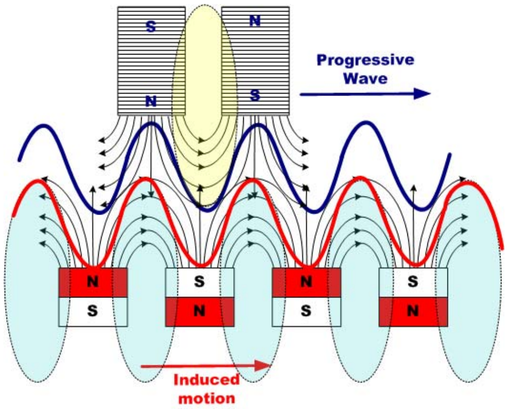

Fig. 3(a) Working principle of the progressive wave method.

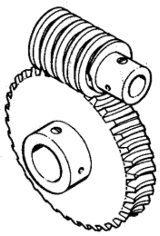

Fig. 3(b) Analogy to the mechanical worm gear.

As this proposed method shows, the basis for realization of motion lies in the generation of progressive wave [20]. Let us consider concretely the method and conditions for exciting this progressive wave in the linear motion as discussed. Fig. 4 depicts a basic configuration of a pair of adjacent stator coil placed adjacent with each other. When electrical AC signals are applied to the stator coils, the AC current through the magnet wires will generate alternating magnetic field. These flexural electromagnetic fields propagate through space as illustrated in Fig. 5.

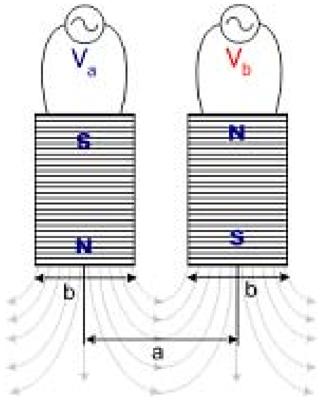

Fig. 4 Basic configuration of stator pole for the generation of progressive wave.

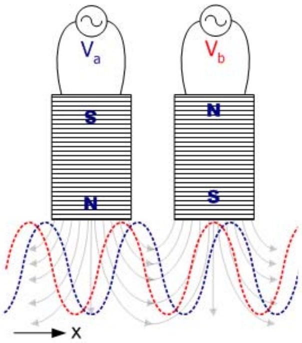

Fig. 5 Propagation of flexural electromagnetic fields.

Progressive wave excited by V_a and retrogressive wave excited by V_b can be expressed by the following equation respectively [22].

$$A\sin(\omega t - kx) + A\sin(\omega t + kx) \tag{1}$$

$$B\sin\{\omega t - k(x+a) + \alpha\} + B\sin\{\omega t + k(x+a) + \alpha\} \tag{2}$$

Where $k = 2\pi/\lambda$ with k, v and λ as the circular wavenumber, velocity and wavelength respectively. Expanding (2) and adopting the following change of variables:

$$-ka + \alpha = \alpha_1, ka + \alpha = \alpha_2 \tag{3}$$

Equation (2) can be rewritten as

$$B\sin\{\omega t - kx + \alpha_1\} + B\sin\{wt + kx + \alpha_2\} \tag{4}$$

By applying the principle of superposition, w can combine the wave equation generated by the two coils. Thus the conditions that only a progressive wave is generated for the combined wave are as follows,

$$\begin{aligned} &\alpha_1 = m\pi,\ \ m\ \ even\ (m = 0, \pm 2, \pm 4.....) \\ &\alpha_2 = n\pi,\ \ \mathrm{n}\ \ odd\ (m = \pm 1, \pm 3.....) \end{aligned} \tag{5}$$

Hence substituting into (3),

$$\alpha_1 = -ka + \alpha = m\pi$$
$$\alpha_2 = ka + \alpha = n\pi$$

Therefore we have,

$$\begin{aligned} a &= \frac{\lambda(n-m)}{4}\quad (m \neq n) \\ \alpha &= \frac{\pi(m+n)}{2} \end{aligned} \tag{6}$$

The equation of combined wave is expressed by,

$$
\begin{aligned}
&A\sin(wt-kx)+A\sin(wt+kx)\\
&+B\sin(wt-kx+m\pi)+B\sin(wt+kx+n\pi)
\end{aligned}
$$

$$= (A+B)\sin(wt-kx)+(A-B)\sin(wt+kx) \quad (7)$$

If we are to input the same magnitude for the electrical signals, in the ideal case, we have A=B and (7) reduces to,

$$2A\sin(wt-kx) \quad (8)$$

As a result, a progressive electromagnetic wave is being generated. If m and n is reversed, the progressive wave will vanished and a retrogressive wave propagates. Hence, the basic conditions are a $= \lambda/4$ and $\alpha = \pi/2$ (n=1, m=0).

The advantages of the proposed method can be summarized as follows:

- Continuous actuation scheme.
- No delay due to induction.
- Directional change controlled by phase shift of input signal.
- Simple strategies with no commutation involved.

With the proposed method of actuation, we can extend to a circular planar surface in order to achieve angular rotation. As illustrated in Fig. 6, by utilizing only three pairs of stator coils, we can essentially achieved 3 DOF motion.

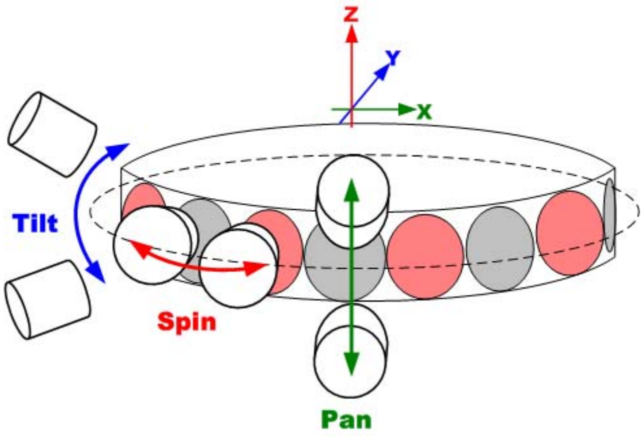

Fig. 6 Generation of 3 DOF motion.

By aligning rotor and stator poles axially, pan and tilt motion can be realized by energizing the respective stator poles. The analysis of the electromagnetic force can be simplified, as the attraction/repulsion force is predominantly in the normal plane. Spin motion can then be accomplished by the proposed progressive wave method and hence achieving 3-DOF in this simple configuration.

IV. VALIDATION

Preliminary testing was conducted using a spherical bearing as shown in Fig. 7. Permanent magnets were placed around the peripheral as poles fashioning the analogous virtual gear profile mentioned earlier. The key advantages of this type of bearing over existing support scheme employed can be sum up as follows:

- No contact between bearing and rotor surface.
- No special surface treatment required on rotor surface.
- Simple installation.
- Calibration possible upon installation.
- As bearing is installed at the center of rotor, the decrease in moment arm will result in lower inertia and friction contributed by the bearing.

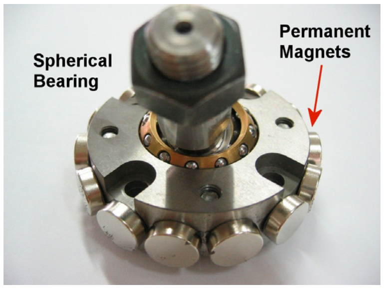

Fig. 7 Spherical rotor.

By arranging rare earth magnets and air core coils as illustrated in Fig. 6, we are able to verify the theoretical aspect of the proposed method. The desired spin motion was achieved as designed. In order to have decoupled 3-DOF motions, we can actuate concurrently the respective stator coils in the pan and tilt direction. Fig. 8 shows the experimental setup to validate the proposed progressive wave method.

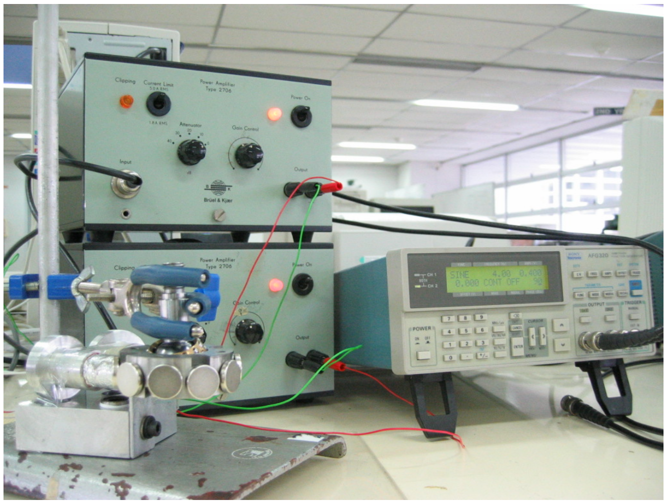

Fig. 8 Experimental setup.

The uniqueness and advantages that this new actuating method offers are as follow:

1. Allows full utilization of usable rotor workspace as poles and adjacent to each other.
2. Directional change can be simply controlled by adjusting the phase of input signal.
3. Continuous motion generated with just a pair of stator poles.
4. 3-DOF motions can be achieved with only six-stator poles design.
5. Higher angular velocity compared to existing design.

IV. CONCLUSION & DISCUSSIONS

A novel actuating principle for a spherical actuator is being proposed. This method of actuation eliminates complicated commutation algorithm in realizing spin motion. By identifying the priorities in the mechanical structure design and utilizing the available space constraints, the proposed progressive wave method is ideal to be implemented in bid for a compact and efficient spherical actuator. Preliminary experimental tests verified and established the viability of this new working principle. To date, there are no commercially available spherical actuators in the industry. This is mainly due to technical hitches owing to its spherical nature that poses challenges not just in terms of control but also in the orientation sensing feedback. Thus understanding the design objectives and requirements, we can utilize the space available for actuating purposes. As mentioned previously, we do not require the full spherical region for practical application of these actuators. Thus, incorporating the proposed actuation method, we can exploit the full potential of the unused planar surfaces as illustrated in Fig. 9.

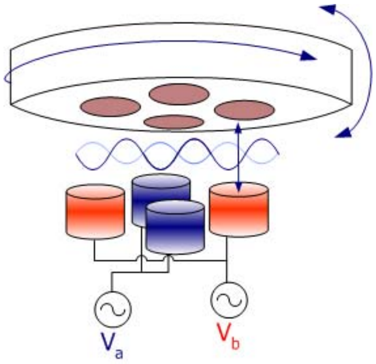

Fig. 9 Utilization of planar surface.

Orientation sensing is another area of interest in multi-DOF mechanism, which essentially provides feedback to the system. The obstacle for the implementation of an efficient and cost effective multi-DOF orientation system is the spherical surface that is required to be sensed. Mechanical encoder promises simple setup but induces unnecessary friction to the structure. With ever increasing demand for smaller and more efficient actuators, contactless sensors are preferred. The prerequisite for this class of sensors will be the need to process the surface to be scanned. In most cases, extensive resources are invested preparing the surface and the resolution is limited. This issue can be surmounted if sensing is to be conducted on a planar surface. This simplifies and avoids extensive resources invested in processing the spherical surface. Contactless sensors can be installed within these surfaces as depicted in Fig. 10. With the proposed progressive wave method of actuation, miniaturization of prototype can be made possible taking one step further into the commercialization of a spherical actuator.

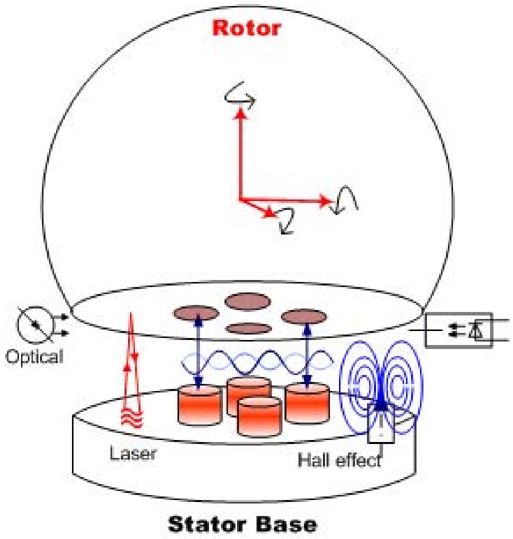

Fig. 10 Schematic of potential sensor applications.

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