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Multi degree of freedom mechanism for multiple application

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***Abstract** - This project presents an active ball joint mechanism. Robots mainly consist of links and joints, hence studying different joints and coming up with new joints will contribute to advancing robots. The methodology used in this project is; Proofing the concept of the Omni-Joint by theoretical analysis and manufacturing a prototype, comparing the following revolute joints; Omni-Joints, Hook's joint, and Ordinary joint. The comparison is regarding; points of singularity, range of field of motion, inverse kinematics, and applying it on different paths using MATLAB and studying the stresses on the mechanism, and design using SolidWorks software in different postures.*

The experimentally results of the innovative gears are to create mechanism with three RDOF The challenge in multi-degree of freedom mechanisms is the range of motion. In this mechanism there is two types of placing the two driving modules. First of them is opposite type 180[deg]. It provides a range of motion of 270, 90, 360 [deg]. The second one is perpendicular type 90 [deg] this range of motion is relatively high compared to other.

Keywords: ball joint mechanism, SolidWorks, MATLAB, spherical gear.

I. INTRODUCTION

Various kinds of mechanisms have been used as a joint which has been applied not only to the industry but also to robots or manipulators. since these mechanisms have only one or two degrees of freedom if these are applied to complex mechanisms such as wrist joint, end effector robot arms, and various other mechanisms it needs multi-degree of freedom, the structure gets complicated due to many links, gears, complex design, and reliability become lower. The classical mechanisms which use a friction wheel for force transmission comprise a sphere and another frictional wheel, but they faced many problems like slippage which affect high torque transmission and positioning accuracy. There is another actuator, which is a three-dimensional extension of the induction motor has been proposed. Although it has high power capability, it still has problems with power consumption, friction, and eddy currents which leads to high temperature. to solve these problems, we developed a multi-degree of freedom mechanism for multiple applications this mechanism has three rotational degrees of freedom based on nonslip gear meshing, the mechanism provides high-torque transmission and reliable positioning without requiring a three-dimensional sensor. In addition, because the actuator and output link can be flexibly arranged, the mechanism can take various configurations. Although the proposed gears have complex shapes, we believe that recent advances in manufacturing technology will enable their practical fabrication. In optimized future designs, the mechanism will gather the joints of a robot or other mechanisms at one point, reducing the energy and resource consumption and improving the economy of robot operation.

II. OVERVIEW

A. Agile Eye [1]

The Agile Eye is a spherical parallel manipulator capable of orienting a camera or a laser pointer with high speed and accuracy in three rotational degrees of freedom for vision applications, The prototype was built in 1993 and has been gaining in popularity ever since. The workspace of the Agile Eye is superior to that of the human eye. The miniature camera attached to the end-effector can be pointed in a cone of vision of 140° with ±30° in torsion. Moreover, due to its low inertia and its inherent stiffness,

This mechanism has two main advantages which are:

- it can achieve angular velocities above 1000°/sec
- it can achieve angular accelerations greater than 20000°/sec2

Which is beyond the capabilities of the human eye.

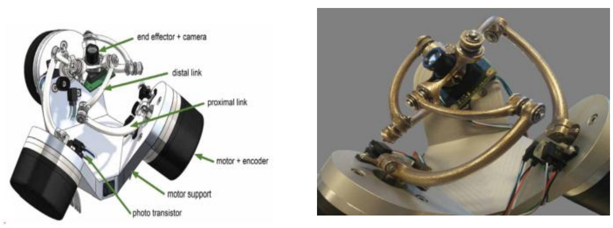


Fig.1 (a),(b) Agile Eye

It has some disadvantages which are:

- low range of motion compared to active ball joint mechanism
- can transfer low torque only

B. Atlas Spherical orienting device using Omni-Wheels [2]

Its orienting concept uses Omni-wheels to actuate the three rotational DOF motions (roll, pitch, and yaw).

The traditional system for force transmission, which depends on friction, comprises a sphere and several strategically placed friction wheels.

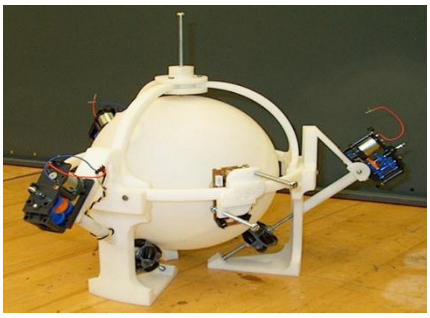


Fig. 2 Atlas Spherical orienting device using Omni-Wheels

This mechanism solves all problem that face the previous project, so the main advantages are:

- provides three rotational degrees of freedom
- reduces the slippage
- provide a high-power transmission.

But it still has some disadvantages:

- It cannot solve friction problem

C. Spherical Stepper for Robotic Applications [3]

stepper motor capable of three-degrees-of-freedom (DOF) motion in a single joint. The most important advantages are that

- The ball-joint-like motor has no singularities except at the boundary of the workspace and can perform isotropic manipulation in all three directions.

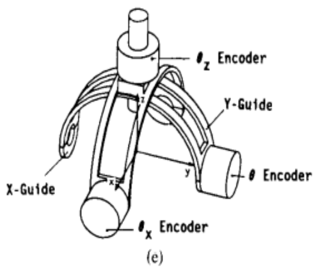


Fig. 3 Spherical Stepper for Robotic Applications

Drawbacks:

- The mechanical design of a spherical induction motor is complex
- Complicated three-phase windings
- Eddy current losses
- Heat generation

D. Spherical Wheel Motor (SWM) [4]

spherical motors where design focuses have been on controlling the three degrees of freedom (DOF) angular displacements with high position accuracy and these are the only two advantages the SWM offers a means to control the orientation of a continuously rotating shaft in an open-loop (OL) fashion The concept feasibility of an OL controlled SWM has been experimentally demonstrated on a prototype that has 8 rotor permanent-magnet (PM) pole-pairs and 10 stator electromagnet (EM) pole-pairs.

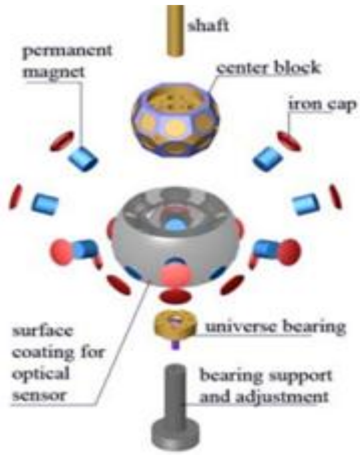


Fig. 3 Spherical Wheel Motor

This (SWM) has a lot of disadvantages:

- complex design
- limitation of working space range
- losses due to eddy current
- heat generation
- low torque
- high non-linearity of the torque

III. OBJECTIVE

The main Object of the work is to understand work system of spherical gear, and creating a mechanism that has three rotational degrees of freedom without slippage and with high position accuracy and large range of motion the design of spherical gear meshing. This mechanism can actively drive three DOF. During meshing, the two gear types interacted through gearing, coupling, and sliding motions, allowing a single MP-gear to constrain or drive two DOF of the CS-gear.

After discussing the main characteristics of our project the designing issues mechanism contains many unique components, such as CS-gear and MP-gear. Although these brought new possibilities, some difficulties are foreseen. Project including:

- Operational Issues of CS-Gear, MP-Gear, and Holder.
- Manufacturing of MP-Gear and CS-Gear.
- Holder and Range of Motion.

A. Operational Issues of CS-Gear, MP-Gear, and Holder.

This section discusses the practical design and operational issues of CS-gear, MP-gear, and holder. Of the meshing between the CS-gear and MP-gear, the gearing motion has properties similar to those of normal gear. The backlash between the MP-gear and the CS-gear in the prototype was 0.13–0.34 [deg] in terms of the CS-gear angle, as shown in Since the MP-gear drives the CS-gear with a wide line-contact, its transmission capacity is considered to be large , even if there are some slots in the CS-gear, which is expected due to the other tooth structure. The transmission efficiency is expected to be similar to a normal spur gear, and the forward and backward efficiencies should always be symmetrical. However , near-pole meshing increases sliding contact, so the transmission efficiency will decrease due to friction. These need to be revealed more in terms of gear engineering.

The sliding motion is a sliding contact behavior that is strongly influenced by friction. Therefore, in practice, the tooth surface should be lubricated with grease, even if it is a resin, to reduce the contact friction with the holder. If there is an error of meshing due to backlash in coupling motion, i.e., an error between the CS-gear and MP-gear tooth line, the notches in the CS-gear may conflict with the MP-gear during the sliding motion. Chamfering to the corner of the CS-/MP-gear teeth will reduce this problem . It is also important to keep a proper backlash. The distance between the MP-gear and CS-gear is provided by the holder and the driving module. The holder in the current design requires some mechanical compliance to allow for thermal expansion, resin swelling, and fabrication errors to keep the CS-gear on a spherical surface. A small preload is applied to hold the CS-gear in place and small variations occur depending on the orientation of the CS-gear. In other words ,the relative distance between the tooth tips of the CS-gear and the inner surface of the holder does not ideally fluctuate. Since the driving modules installed in the holder also variate with the holder, the distance between the CS-gear and the MP-gear is kept constant. However, in practice, the variation of the relative distance may not be zero. This is a complex problem determined by the distribution of mechanical compliance of the holder, the mounting position of the driving module, the preload, and the amount of fabrication error. Adopting a typical ball joint design approach will contribute to a more appropriate holder design

B. Manufacturing of MP-Gear and CS-Gear.

Establishing a manufacturing method for a CS-gear and MP-gear is one of the biggest challenges. 5-axis machining centers are a viable solution for both metallic and resin materials. On the other hand Using a 3D printer is a good way to fabricate, this mechanism. is an early prototype of this project and MP-gears, which were manufactured by 3D printer for theory validation and are confirmed to work. Also, the MP-gear's shape generation algorithm is already established and the module and number of teeth can be easily changed.

In the case of metal 3D printers, a presence of a rough surface due to the sintering of the metal powder is not suitable for CS-/MP-gear. On the other hand, it is remarkable that combined machining centers and metal 3D printers have emerged in recent years. The problem may be solved by cutting only the tooth contact surface thin in post-processing

C. Holder and Range of Motion.

The CS-gear of the prototype must be held by a holder. Therefore, if there is an output axis ,the range of motion is limited, Such systems can be found in a friction wheel, a spherical motor, and an ultrasonic system. On the other hand, a linkage or differential mechanism has no such limitations. One way to increase the range of motion is to remove the bottom part of the opposite type prototype's holder. This reduces the contact area between the CS-gear and the holder. Thus, the stiffness is one of the challenges, but it allows for a range of motion of 360, 90, 360 [deg]. Another way is to design the angle between the driving modules to be small. The prototype's angles are 90 and 180 [deg] but can be placed at a minimum angle of 60 [deg]. If a mechanism to prevent the CS-gear drop out is installed and the overhang is removed from the holder, the range of motion in this mechanism will be extended to approx.180, 180, 360 [deg]. We expect that the linkages, magnets, or mobile spherical shells provide auxiliary holding for the CS-gear. Holding the CS-gear in a passive gimbal mechanism is one valid method. However, the singularity of the linkage mechanism will be an issue. On the other hand, a combination of a CS-gear containing a ferromagnetic material and a holder with permanent magnets is an alternative .In this case, we need to consider the friction caused by magnetic forces and the permissible load of the hand. However, the configuration of the mechanism is relatively simple. In addition, there is one option to hold the CS-gear with a movable spherical shell structure Although many challenges are foreseen in this design, it is possible to hold the CS-gear with surface contact .There are many challenges in designing the holder, but due to the flexibility of its design, we believe our graduation project has a high potential for the near future.

IV. WORK METHODOLOGY

This mechanism based on two innovative types of gears which are CS-gear and MP- gear, CS-gear is supported by a holder and two driving modules of an MP-gear .The MP-gear has a unique tooth shape that meshes with the CS-gear and is driven with two RDOF by the driving module .Thus, this mechanism is driven by four motors. If applied to a robot arm, the holder and the two driving modules are fixed to the same link B on the root side, and the CS-gear is fixed to link H on the end side. Consequently, the mechanism operates like an active ball joint with three RDOF between links B and H. It enhanced by interactions of spherical gears. The gear-based joint drives three rotational degrees of freedom without slippage which is a common problem which face the majority of previous projects. The capabilities were inspired by the unique interactions between two different gears [the cross spherical gear (CS-gear) and monopole gear(MP-gear)] and the superimposition of those interactions by the CS-gear's quadrature spherical tooth structure.

A. *Cross spherical gear*

The CS-gear is formed by engraving two axisymmetric tooth structures on a spherical material. Specifically, the tooth structure is first engraved on the surface of the sphere around the x-axis like the tooth type is a tooth of ordinary spur gear. Next, by additionally engraving around the y-axis, a quadrature spherical tooth structure around both axes is formed on the spherical surface. So, by revolving the spur gear around the two perpendicular axes the quadratic tooth structure is formed. This mechanism uses CS-gears, but basic spherical gears are sometimes used for convenience when explaining the principle of the mechanism. The module m_{sph} of the involute tooth profile of the CS-gear is unconstrained. In contrast, the number of teeth z_{sph} is subjected to two constraints.

1) The number of the tooth must be even.
2) The x and y-axes are located in the center of the valley or peak of the tooth.

These conditions are necessary to avoid obtaining incomplete teeth due to the interference of the two tooth structures and to mesh with the MP-gear.

The pitch circle diameter d_{sph} mm, the addendum circlediameter $d_{a.sph}$ mm, and the tooth depth h_{sph} mm of a CS-gears are defined as follows, just like the typical spur gears:

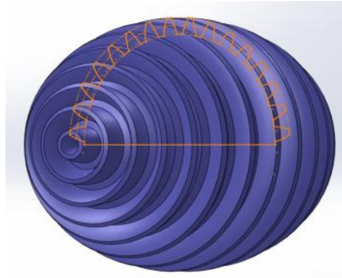


Fig. 4 spherical gear

$$d_{sph} = m_{sph} * z_{sph} \quad 1$$

$$d_{a.sph} = d_{sph} + m_{sph} \quad 2$$

$$h_{sph} = 2.25m_{sph} \quad 3$$

B. *Monopole gear*

The MP-gears have a unique tooth structure, the pole, which can mesh with the CS-gears. When the z- and x-axes are aligned with the rotational axis and the pole an MP-gear is symmetric in the x–y plane

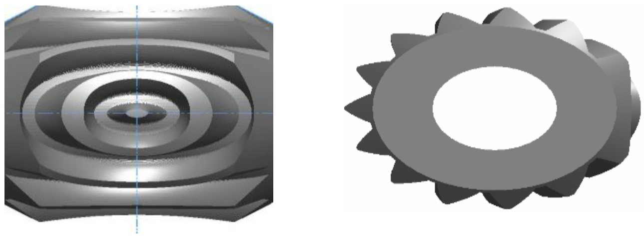


Fig. 5 Monopole gear

The module $M_{mpl}$and number of teeth $Z_{mpl}$of the profile are, respectively given by :

$$M_{mpl} = M_{sph} \quad 4$$

$$Z_{mpl} = Z_{sph}/2 \quad 5$$

One pole of the MP-gear can mesh to two poles of the CS-gear in one complete revolution. To explain the tooth structure of the MP-gear is shaped similarly to a basic spherical gear and is formed by rotating a typical gear profile around a structural axis The gear profiles of the MP-gear are arranged on the same plane and mesh like a typical pair of spur gears. If the distance between the centers is fixed at some appropriate length, the system behaves as a planetary gear mechanism. The length of the carrier R_{cr}mm, the revolution angle of the planetary gear φ_{cr} *rad* around the sun gear, and the rotation angle of the planetary gear φ_{hb} *rad* are, respectively ,defined as follows:

$$R_{cr} = \frac{M_{sph}(Z_{sph} + Z_{mpl})}{2} = \frac{M_{sph}}{2} \times \frac{3Z_{sph}}{2} = 0.75d_{sph} \quad 6$$

$$\varphi_{hb} = \frac{\varphi_{cr}}{2} \qquad 7$$

$Where\ (0 \leq \varphi_{cr} < 2\pi)$

The spherical gear is basically a rack cutter it engrave the tooth structure of cross-spherical gear into the mono-pole.

As the two poles of the basic spherical gear are symmetrical, an MP-gear with half the number of teeth and only one pole can unlimitedly mesh with the basic spherical gear. This behavior appears to draw a polar orbit with respect to the CS-gear Moreover, an MP-gear can mesh not only with the basic spherical gears but also with the CS-gears possessing two structural axes.

The large tooth width of the MP-gear effectively constrains the CS-gear, thus stabilizing "coupling motion." The tooth width is determined by considering the size of the "Driving module"

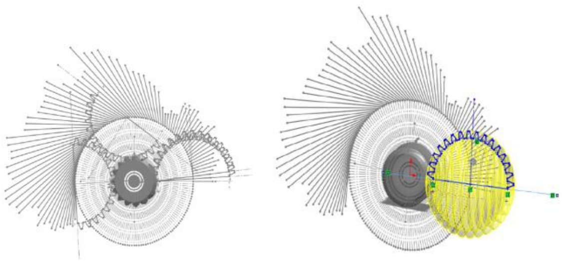


Fig. 6 Spherical gear diagram

This mechanism contains 4 motors each module has two motors one responsible for roll motion and the other for pitch motion these motion provide the cross spherical gear coupling , gearing and sliding motion.

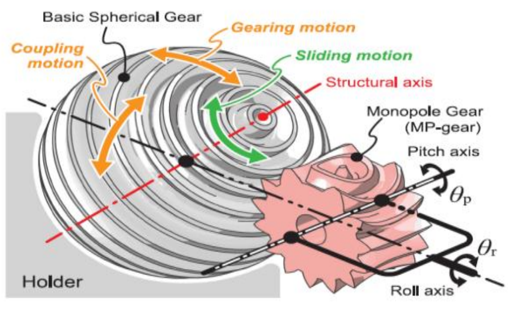


Fig. 7: Basic spherical gear

We use closed-loop system Position Control of the DC Motor using PID Controller is a proportional–integral–derivative controller (PID controller). PID controller calculates an "error" value because of the difference between a measured process variable and therefore the desired point. The controller attempts to reduce the error by adjusting the method of control inputs.

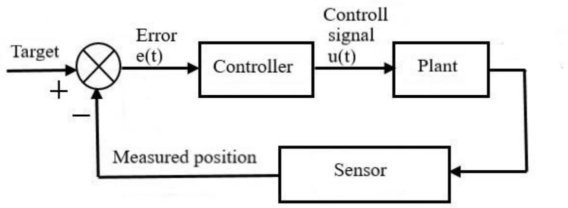


Fig. 8 Block diagram

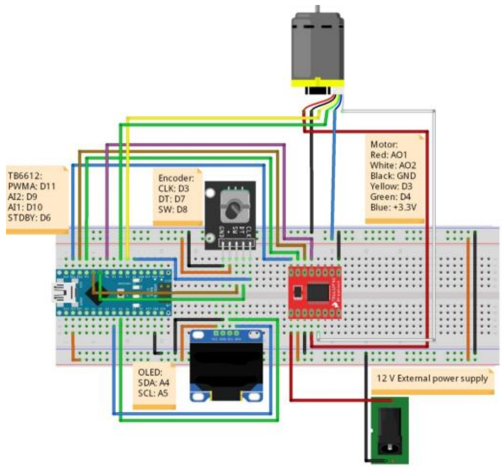
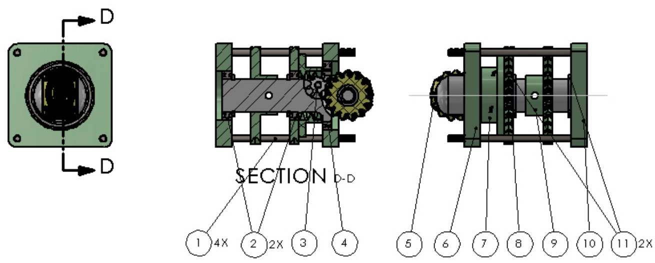
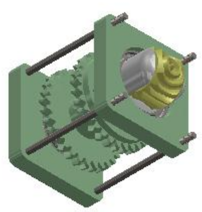


Fig. 9 Schematic diagram of the connections

C. Design model

This mechanism consist of 2 driving modules and cross spherical gear, first module driving module. The driving module contain an innovative gear called monopole gear its dimension illustrated in the following figures.





Item no.	Name	Quantity	Description
1	alen bolt	4	M5*10
2	Bearing	2	skf 6805 2z/c4
3	spur gear	1	module:2 , teeth:8
4	bearing	1	skf 6808 2z/c4
5	Monopole	1	Module 2
6	front plate	1	
7	inner worm gear	1	
8	double helical gear	1	module :2 , teeth:30
9	double helical gear with hub	1	module :2 , teeth:30
10	Rear plate	1	
11	Snap rings	2	

Fig. 10: 3D CAD model

The second module is cross spherical gear, the part of our mechanism is the cross spherical gear where the output link is fixed on the design methodology is explained before the following figure illustrate its dimensions.

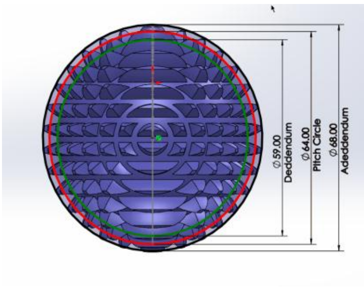


Fig. 11: 3D CAD model spherical gear

D. Experimentally operation test

Experimentally test confirms the characteristics of the mechanism mentioned in the introduction, i.e., three RDOF, absence of slippage and providing high range of motion Then, the corresponding results and the practical issues of the mechanism are discussed.

The accuracy of output link positioning is one and its high motion range (in its two types opposite & perpendicular) will be tested experimentally in this section to confirm whether the theoretical motion range of the system is achievable in practice. OptiTrack V120 trio tacking system is used in this experiment to measure the orientations on the output link (tracking mark)

First the target points were regularly arranged in the configuration space based on the Euler angles in within the motion range of the output link. Next the prototype was operated to reach those points.

Finally the orientation of the output link was measured by a motion-capture system that originally had been coordinated8 to match the Euler angles in the prototype.

Both perpendicular- and opposite-type prototypes were employed in this experiment. the measurement area was set as follows: Roll=±90, pitch=±45 (perpendicular type) or ±30 (opposite type), and yaw = 0 to 270. The target points were set in the area at equal intervals: Roll and pitch= 15 and yaw = 90. To reveal the continuity of positioning, the position measurements were made at each target point, approaching the roll, pitch, and yaw from both the positive and negative sides (±15 [deg]) taking the measurements at each point.

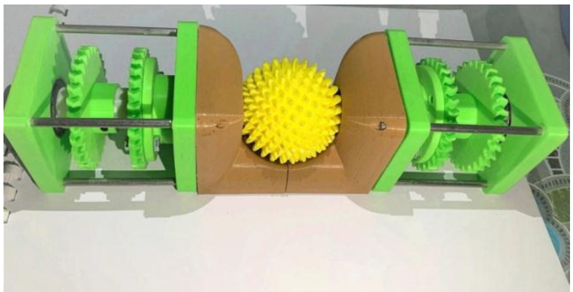


Fig. 12: 3D Print prototype

Positions of the tracking marker attached to the output link were measured To obtain the results of one measurement, an average of 120 measurement data during one second was used.

In this section trajectory tracking will be discussed by experiment which verify the transient response of the mechanism's prototype as it moves from one orientation to the other: The CS-gear's orientation is measured by following the trajectory of a straight line set in the r, p, y [deg] three-dimensional configuration space. If the tracking of the prototype is good, the measurement points plotted in three-dimensional space should be well linear.

To set up the measurement trajectory, we prepared reference points. The trajectory runs in sequence from P0 to P8. In one straight movement The fastest rotation is set to 90[deg/s], while the other two rotation speeds are adjusted to synchronize. Each reference point has a stopping time of 1s. The CS-gear orientation was measured with a period of 120 Hz.

Table 1: measurement trajectory

measurement trajectory	P0	P1	P2	P3	P4	P5	P6	P7	P8
r (around roll axis)	0	-90	-90	90	90	90	90	-90	-90
P (around pitch axis)	0	-45	-45	45	-45	45	-45	45	45
Y (around yaw axis)	0	0	360	0	0	0	360	360	0

V. RESULTS

The results of the mates of innovative gears are to create mechanism with three RDOF The challenge in multi-degree of freedom mechanisms is the range of motion. In this mechanism there is two types of placing the two driving modules. First of them is opposite type 180[deg]. It provides a range of motion of 270, 90, 360 [deg]. The second one is perpendicular type 90 [deg] this range of motion is relatively high compared to other mechanisms and since our mechanism is a gear based mechanism it reduces slippage and provide high position accuracy as well as high torque and reliable transmission and those problems occur in many of similar mechanism that provide multi degree of freedom like our project.

A comparison of these movable ranges is shown in the following table 2:

name	type	θ_1	θ_2	θ_3	Ref.
Our project opposite type	Gears	270	90	360	
Agile eye	Linkage	140	140	30	[6]
Briglen et al.	Linkage	90	45	45	[15]
Hess – Coelho et al.	Linkage	140	140	360	[16]
Hammond et al.	Linkage	180	180	360	[17]
Kaneko et al.	Motor	30	30	360	[18]
Yano et al.	Motor	90	90	360	[19]

VI. CONCLUSION

This study proposes a new mechanism based on spherical gear meshing, this mechanism can actively drive three DOF. During meshing, the two gear types interacted through gearing, coupling, and sliding motions, allowing a single MP-gear to constrain or drive two DOF of the CS-gear. This study proposes that the three DOF of the CS-gear are achieved by driving two MP-gears meshed with two phase-different tooth structures. This idea is reinforced by the mechanistic equivalence of the gear mechanism and a linkage mechanism. It also suggests that the mechanism's capability of is independent of the positional arrangement of the MP-gears (driving modules).

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