DESIGN STRUCTURES AND DRIVING MECHANISMS OF SPHERICAL ROBOT

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ABSTRACT

In this paper, brief descriptions of the different driving mechanisms that can be incorporated in a spherical robot are explained along with their advantages and disadvantages. We have mainly focused this paper on widely used driving mechanisms such as hamster mechanism, pendulum–driven mechanism and control moment gyroscope (CMG) mechanism. Spherical robot is an upcoming product that is used in the market for educational purpose, surveillance, spying, monitoring and in variety of applications. The below explained mechanism are utilized in the construction of spherical robot for better performance and accuracy in number of applications.

Key words: Spherical Robot, Internal Driving mechanisms, Hamster, Pendulum driven, Control Moment Gyroscope.


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1. INTRODUCTION

A robot which has an external spherical shape or which represents the shape of a ball is called as a spherical robot. It basically consists of an outer spherical shell which acts as the body of the robot and inside the spherical shell the respective mechanism is placed which is the main operational unit and is used to control the motion of the robot. It takes a circular motion i.e. it rolls like a normal ball to move over surfaces. It works on spherical co-ordinate system. The outer shell of the spherical robot can be made using different materials depending on the area of application. It is generally made of a hard-firm pellucid material but it can also be made of translucent or supple material according to the need of application or drive mechanisms. Spherical robots can be self-operational or remote controlled.

Mostly in all spherical robots, interface between internal driving unit and external control unit is wireless because of movability and enclosed nature of the outer shell. A rechargeable battery is placed inside the robot which acts as the power source for driving motors and other electrical connections. Whereas, in some robot’s solar cells are located on the outer shell of the sphere. Spherical robots are more advanced than Cylindrical and Cartesian robots because they can be easily controlled without any complications. They provide faster planar mobility in every direction than any other robots. They showcase high mobility also on uneven
Surfaces and terrains and they are not harmed by collisions with obstacles while travelling even in harsh environment as the spherical structure offers a strong protective shield to it. Spherical robots have high stability, it gets back to its normal position even after high irregular motions thus avoiding overturning and loss of control problems as in case of Cartesian and Cylindrical robots. The driving mechanisms, sensory devices and control devices all are placed inside the robot. This makes the spherical robot more dominant over traditional wheeled or track mobile robots for various applications.

Among various types of robots, spherical robots have become greatly popular in the last decade because they have several advantages over regular cylindrical robots. There is only a single point of contact between the spherical shell and the ground surface resulting in less amount of friction during motion. Hence, they are able to save energy for movement. The spherical exo-skeleton shell protects inner structure from external shocks or dust and it can even work in highly constrained environment. The external structure can also be made gas or liquid proof so as to protect the internal electrical connections from electrical shock and damage. Also, there is no probability for the robot to tip over, turn over or to lose its mobility. Spherical robots are providing a transpiring research field because of its attribute to be holonomic with a concealed structure and its ability to rebound from collisions easily by even providing an omnidirectional movement.

2. HAMSTER MECHANISM

Hamster mechanism is also known as Barycentre offset principle, where barycentre means the center of mass of the spherical body or sphere [1]. Hamster mechanism is the simplest mechanism of all. It is basically a rotating wheel similar to wheeled vehicle in which a counter balance weight is placed inside the spherical body as shown in Figure 1 and this weight moves which results in locomotion of the robot.

![Figure 1 Prototype of Hamster Ball design](image)

In the Barycentre offset principle mechanism, the centre of mass i.e. barycentre is shifted to produce a desired motion [1]. Mobility of the spherical robot is deployed by interrupting the system equilibrium condition and hence unbalancing the structure [2]. The assembly is moved by a motor driven wheel or a small wheeled vehicle known as hamster that can be moved to give motion to the robot[1]. To transform this in practical, a control system is designed and integrated inside the spherical body to move this robot in predetermined way. Control is based on the kinematic and dynamic analysis of the rolling mechanics [2].

An early design which uses the Barycentre offset principle is the hamster wheel ball. A small wheeled robot or vehicle is placed inside the sphere and the weight of the robot or vehicle provides enough energy to drive the robot when it moves. Single-wheeled or multi-
wheeled designs can be placed inside the sphere. But practically, a four – wheeled design will provide different motion curves leading to better mobility [1].

Consider a spherical ball resting in its equilibrium state, the mechanical internal mass which acts as internal driving unit is stable and resting at single point which is at the center of mass position of the sphere. When the mechanism of internal mass moves from its equilibrium position, due to change in the distribution of the mass inside the ball the center of mass point will also change, this will lead to the motion of the sphere i.e. rolling at another equilibrium position [1].

This counter weight/ balance can be replaced by a single wheel for purpose of motion [2]. The major requirement to be fulfilled for this mechanism is that the wheel should be in constant contact with the outer shell of the spherical robot either by a stable mechanism or with the spring - loaded mechanism technique [1].

In stable mechanism technique, a single bar is attached at one end to the sphere end and at other end the wheel is connected, this is the simplest technique [1]. But the drawback of stable connection is that after a period of time the contact between the wheel and the inner shell of the sphere may get loose, therefore to avoid this, another technique called spring – loaded mechanism technique is used.

The spring – loaded mechanism technique is basically used to provide elasticity which is done by pressing or pulling a helical metal coil against the body of the robot[1]. Figure 2 shows the diagram of spring – loaded mechanism. Here a bar and a spring are connected at the upper end of spherical robot and compressed /force against the shell and this will force the wheels to be in continuous contact with the outer shell. The top of the helical coil is connected with the 3-degree of freedom (DOF’s) ball bearing that allows it to travel along the internal surface of the shell with small amount of friction [1].

This mechanism is also known as Internal Drive Unit (IDU).The major advantage of IDU is that it sustains the contact between the wheel and the inner shell and due to this the speed of the ball can be controlled by the motor speed and even at the low speed the directional control of the system can be made moderate. To avoid continuous friction which can result in degradation of performance therefore here the wheel that is to be used can be made up sponge to avoid friction.

[Image: Design structure of spring – loaded design]
The momentum vector can change because of an active control which occurs due to the rotation of the driving wheel around the vertical axis of the IDU, or it can change because of imbalance caused by some disturbances on the outer surface [1].

There is one more design that uses the principle of barycentre offset. This design is formed by integrating the hamster wheel and IDU design. It can be explained as a universal wheel type system. Here, combination of wheels can be attached to the interior drive mechanism. Figure 3 illustrates this mechanism with design structure. This will help in providing free movement of rotation on the inside of robot. Two DC drive motors can be incorporated together to control the movement of robot around its axis; one motor is used to control the alignment of IDU and one motor is used to control the speed of drive. This enables the spherical robot to locomote with zero turning radius providing more holonomy than other robots. The robot’s velocity is controlled by the angular velocity of driving wheel. The translational velocity of robot is directly proportional to the spinning speed of the wheel hence the weight of IDU is not the only factor that will control the locomotion velocity. This robot is capable to travel in sand, water as well as on a small slope but it might have higher loss of energy due to the friction from sponge wheels as well as its inefficiency to travel down a slope which is directly depended on the motors used [1].

![Figure 3 Design structure of Universal Wheel Mechanism](image)

1 – Motor, 2 – Motor, 3 – Sponge wheel

3. PENDULUM – DRIVEN MECHANISM

The pendulum driven spherical robot manifests a constantly changing behavior which is designed for reconnaissance and an uneven terrain environment [3]. It has three degrees – of – freedom (DOF’s) and is non – holonomic in nature [6]. The movement is actuated by unconventional moment and inertial moment which is generated by the pendulum. All the elements are placed on the equator of the robot and driving is done using a counterweight. The counterweight i.e. pendulum, is designed to stay at the bottom of the shell and the shell revolves beneath it, causing momentum [8]. Compared to other mechanisms, this mechanism puts limited restrictions on the design structure of the shell. Propulsion is achieved by shifting the centre of gravity using single weight or multiple weights [3]. The basic mechanism of one – pendulum driven spherical robot is illustrated in Figure 4.

A pendulum is basically a mechanism in which a weighted bob is attached to a massless rod from a frictionless pivot so that it can move freely in back and forth motion. When a pendulum shifts /moves sideways from its equilibrium state, a restoring force due to gravity acts on it and it causes a motion of acceleration towards the equilibrium state [1]. Hence this restoring force affects the pendulum’s mass thus resulting it to oscillate in back and forth
motion. This mechanism is implemented inside the shell of the spherical robot. A fixed shaft through centre of the shell with a rod and a weighted bob that rotates around the shaft is incorporated inside the shell of the robot and is known as the pendulum model. This pendulum model when rotates inside the robot shifts the centre of mass from equilibrium position and the robot begins to roll. There are two motors that drive the pendulum and rotate it about horizontal axis and vertical axis. According to the movement of the pendulum in left or right direction the robot will locomote in the corresponding direction. The amount of torque that drives the robot is directly proportional to the weight of the bob [1]. But as the weight of the bob increases the capability of the spherical robot to go up on a steep slope increases. Practically, the spherical robot with pendulum mechanism can roll up to 30-degree steep slope [1].

![Design structure of one – pendulum spherical robot](image)

**Figure 4** Design structure of one – pendulum spherical robot

However, a heavier weighted bob means a heavier spherical robot. But in turn it produces more torque to drive the robot. The mass displacement is dependent on the axis of rotation (z-axis) and the angle of rotation (theta) which is due to weighted bob [1]. Here one drawback is movement of outer shell of robot is non-holonomic i.e. the movement is associate with a turning radius. Hence, as the radius of shell increases it leads to a heavier weight bob and output torque increases. This requires larger overall energy to move.

In single – pendulum spherical robot, pendulum is located at the centre. This leads to two movement paths of pendulum. One path (P1) is produced by the rotation of the horizontal centre axis and the other path (P2) is produced by the rotation of the pendulum [9]. Path P1 is perpendicular to the horizontal axis and has a limitless motion range [9]. Whereas, path P2 is parallel to the horizontal axis and has a limited motion range as the pendulum and the horizontal axis belong to the same plane [9]. Hence, in single – pendulum driven spherical robot the direction driving capacity is restricted. To overcome this, a double – pendulum spherical robot was designed. The movement of the pendulum along with its axis for one – pendulum system and two – pendulum system is explained in Figure 5 and Figure 6 respectively.
A two-pendulum structure was thus designed so as to overcome the difficulties faced in the one pendulum structure. A two–pendulum driven structure has four driving directions – left, right, forward and backward [3]. Each pendulum can rotate independently without any intervention from the horizontal axis. It can steer its driving direction and change its driving direction perpendicularly while locomoting [9]. This allows the robot to move omni-directionally.
Figure 8 shows the two pendulum structure used in the KisBOT-II robot, generally the rod on the auxiliary axis of this drive system is a straight line but the KisBOT-II uses a curved line structure. KisBOT-II robot allows internal mechanics to rotate about an axis orthogonal to the axis of pendulum movement. The figure(b) shows the top view of the cross-shape frame placed at the horizontal axis of the outer spherical structure. When the sphere is in ideal state i.e. it is now moving and still at one position, the load or mass attached to each pendulum will aligned vertical to the center of the sphere due to which the center of mass is balanced and there is no movement of the robot. The structure is designed such that the motion of the two axis is orthogonal to each other. Due to the space in the sphere for the movement of the pendulum it is used to disbalance the sphere for motion control and the main axis is used to rotate the sphere. As both the axis do not disturb each other motion due to the orthogonal arrangement they can be controlled and used simultaneously [12].

**Figure 8** Motions in two pendulum driven spherical robot

4. **CONTROL MOMENT GYROSCOPE**

The Control Moment Gyroscope (CMG) uses Conservation of Angular Momentum (COAM) principle. In CMG method multiple motors are connected and using COAM principle axial rotation is achieved along with stability and good control over the motion, the only problem with the CMG mechanism is its complex design which limits its use in regular applications, mostly CMG is mechanism is used for planetary exploration and other complex operations.

A way of storing angular momentum (energy) inside the spherical robot so as to increase torque temporarily was designed known as the control moment gyroscope (also known as flywheel effect). It will allow spherical robot to climb more steeper inclines and ascend taller obstacles. Angular momentum is a vector (direction and magnitude) of the flywheel and it is a function of moment of inertia of the flywheel [7]. It utilizes the angular momentum from the flywheels without disturbing the kinetic energy. It requires very less power to generate output torque in the desired direction. The applied flywheel tilting torque is orthogonal to flywheel rotational axis and desired output axis along with the precession output torque which helps the sphere to move forward. When CMG is inclined to utilize the angular momentum, they retain the speed of the spherical robot in the absence of friction as none of the kinetic energy is shifted to the outer shell [7]. When a CMG is spinning and the angular momentum is not utilized, the output angular momentum is zero and the spherical robot can roll normally. Here the relation between the output torque and tilt rate is important to produce a significant amount of torque in a particular duration of time towards the desired direction [7].

A control moment gyroscope is used in this mechanism. The control moment gyroscope is used to provide momentum exchange so that it can produce huge/enormous output torque on the shell of spherical robot. A CMG consists of a flywheel that rotates at a constant velocity respective to the CMG frame. The rotational axis of the flywheel varies about a perpendicular
axis to its rotational axis. This perpendicular axis is known as gimbal axis. The amount of variations of angular momentum between CMG and outer shell of spherical robot is dependent on the gimbal velocity. An undesirable effect of changing the rotational axis of flywheel is that there can be inclination where no output torque can be provided in a certain direction. This inclination leads to singularities in control laws [7]. In spherical robot a three-axis gimbal set, which are pivoted support that allow rotation of flywheel on single axis, which is called as a gyroscope is placed inside the shell. It is used for sustaining/estimating orientation and angular velocity. Figure 9 shows an simplified design structure of CMG driven spherical robot.

![Figure 9 Structure of CMG driven spherical robot](image)

In spherical robot a fixed-output-gimbal device is used to maintain a desired attitude or pointing direction using gyroscopic resistance force. A gyroscope is incorporated in spherical robot with four motors. These motors are connected in feedback with the gyroscope. When spherical robots rolls in a particular direction and it wants to change its path of direction, DC motors give this feedback to the gyroscope. The gyroscope then changes its angle of rotation or orientation towards the desired path and this results in the change of path of the spherical robot. This is called as angular momentum. Hence, the process of orientation occurs repeatedly as soon as a feedback signal gets generated from dc motors and then applied to gyroscope. Thus the laws of conservation of angular momentum can be used to control the spherical robot. Here, angular velocity of CMG is directly proportional to the output torque.

![Figure 10 Details of CMG design mechanism](image)
A CMG has reaction forces in three spatial dimensions [7]. If a CMG spinning about X-axis and rotated above Y-axis then the output torque will be produced in Z-axis. Although this feature is beneficial, it also causes control issues. According to the design of the spherical robot, accuracy in the torque can be utilised to regulate or increase the robot’s angular momentum. However, if the design neglects this extra dimension it may guide the robot in an unwanted direction. Thus, this design can utilize counter rotational force generated when rotating a CMG slower or faster [7]. A uni-directional COAM and a tri-directional COAM was then further incorporated in the design to provide precision torque [1]. The magnitude of torque produced in single axis designs is monitored by the amount of acceleration of spinning wheel [1]. However, in triple axis designs, the precision torque is monitored by the product of angular velocity and rotational acceleration [1]. This mechanism should be incorporated with heavy electronics to provide better accuracy in the locomotion of the spherical robot.

5. CONCLUSIONS
In above discussion we have explained in detailed the three most common types of mechanisms which are placed inside the sphere for controlling and driving the motion of the sphere. Initial spherical robot was developed using the hamster mechanism but due to its various drawbacks for controlling the motion and rotation of the robot other mechanisms were designed depending on the purpose of application and its deployment. Several advancements were made in the hamster mechanism as discussed in the paper but the required controlled motion and stability during rotation was not achieved. Therefore hamster mechanism is widely used for making spherical robot for education, gaming and entertainment applications. For pendulum mechanism two different mechanisms are discussed in the paper. In single pendulum mechanism the control for the motion of the robot was more better but stability while motion and single point axial rotation were the drawbacks which were observed. Another mechanism which was developed and designed by modifying single pendulum mechanism. It was seen that the motion control and stability during motion was able to achieved but the axial rotation issue was not resolved, but using proper electrical feedback axial rotation using minimum space is possible. Pendulum mechanism is widely used in many application such as for surveillance and operations in hazardous environment. While in CMG, multiple motors are to be used to achieve precision torque with proper feedback. It incorporates the principle of COAM. The main condition to be fulfilled is that the flywheel in the gyroscope along with its gimbals should provide accurate motion via feedback. Hence, the feedback mechanism should give as precise output as possible.

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