Geometric and control of a spherical mobile robot

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Abstract: -Mobile robots have been traditionally designed with wheels and few have explored designed with spherical exo-skeletons. This paper described a prototype and analytical study of a spherical mobile robot which is driven by two internally mounted motors. These motors which are located on the 2-DOF robot joints, induce the ball to move to arbitrary positions. Internal motors will move the mass point of the inner mechanism, thereby moving the robot. The kinematic model of spherical mobile robot will be derived in the quasi-static mode while the dynamic model is developed by Kane's method. Finally a PI and fuzzy controller are proposed separately and their deal with this problem is compared. The effectiveness of the proposed method is shown via simulation.

Key-words: spherical mobile robot - kinematic - dynamic - PI controller - fuzzy controller

1 Introduction

The study of Spherical Mobile Robots has its foundation in the belief that there are certain applications where the rolling ability of the robot is advantageous compared to traditional, car-like mobile robots. The advantages are that they are more versatile; less exposed to physical conditions and has a higher resistance towards object collisions. Spherical mobile robots are a special case of what is known as exoskeleton robots, which are robots with an external skeleton. The external skeleton provides efficient cover for driving mechanisms and sensory equipment. Several of the designs have already been tested by different researchers worldwide. Some of the designs have proved inadequate or unsuitable for different reasons, giving some indications as to what are the important physical characteristics for different purposes. In general, most of these efforts have focused on motion planning and control.

Bicchi decided for a design using a two wheeled car that rests on the sphere shell only by its own weight [1]. This rendered the robot rather sensitive to external perturbations such as dents in the floor or obstacles. Halme used a similar car-like structure inside the sphere, but also incorporating a horizontal beam connected to a free-rolling balance wheel in the roof [2]. Bhattacharya experimented with a symmetrical robot using two identical half-spheres being driven by conservation of angular Momentum [3]. By using two identical rotors for propulsion and one rotor for turning the robot manages is quite maneuverable. Mukherjee has patented a system where there are no wheels used for propulsion [4,5]. A system of pancake-motors is mounted to non-symmetrical orthogonal axes, and moves along their respective axes and thereby move the mass centre. Heggelund built a prototype based on the gimbals principle which was the basis for this project. Due to mechanical difficulties, the inner drive unit was implemented with only a half circle inner gimbals ring [6]. This meant the robot was subjected to nonholonomic constraints, and therefore had similar moving pattern as traditional mobile robots. This was therefore considered uninteresting for further treatment.

Unfortunately none of the projects have published enough experimental data or analytic results to make any design comparisons rewarding. As a matter of fact, only one of the papers actually includes experimental results, while the others theorize and simulate their concepts.

This paper presents a different mobile robot class that can achieve many kinds of unique motion, such as all direction driving and motion on rough ground, without great loss of stability. The structure adopted for the robot presented in this paper is one of a spherical mobile robot, which can be seen in Fig. 1.

To make the ball move, a mobile mass is placed within the cavity of the ball. To implement motion, we built a mechanism with an inner mass moving by means of two links. This links rotate by two mutually perpendicular rotors attached to them. This mechanism enables the robot to use the effect of the gravity and the principle of angular momentum conservation however the principle of angular momentum conservation is not well suited for irregular terrain, where unexpected external momentums can appear but in some situation it can cause high acceleration and be useful.

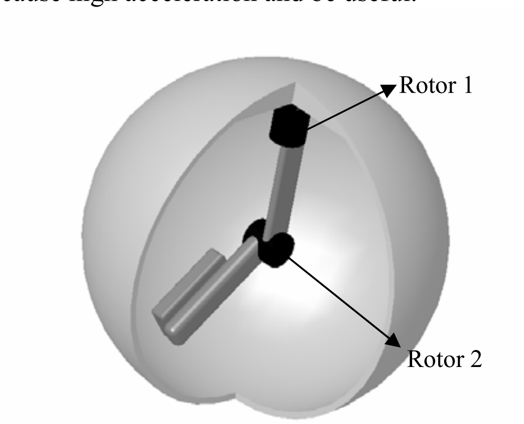

Fig.1 Prototype of the spherical robot.

2 Kinematic model

The configuration of a sphere rolling on a flat surface can be described by the two Cartesian coordinates of the center of the sphere, and three coordinates describing the sphere orientation. In Fig.1a the center of the sphere is defined by point Q; the orientation is described by points P and R, where P is an arbitrary point on the surface of the sphere, and R is an arbitrary point on the equatorial circle, defined relative to P.

To obtain a kinematic model of the sphere, we denote Cartesian coordinates of the sphere center by $Q \equiv (x, y)$. We adopt the $z-y-z$ Euler angle sequence (α, θ, ϕ) to represent the orientation of the sphere. We first translate the xyz frame to the center of the sphere and rotate it about the positive z axis by angle α, $-\pi \le \alpha \le \pi$, to obtain frame $x_1y_1z_1$ .we rotate frame $x_1y_1z_1$ about the y_1 axis by angle $\theta, -\pi \le \theta \le \pi$, to obtain frame $x_2y_2z_2$. The point P is located at the intersection point of the z_2 axis with the sphere surface. The $x_2y_2z_2$ frame is rotated about the z_2 axis by angle ϕ to obtain frame $x_3y_3z_3$. The point R is located at the intersection point of the x_2 axis and the sphere surface. Then we rotate the $x_3y_3z_3$ about the z_3 by angle γ_1 to obtain frame $x_4y_4z_4$ and finally rotate the $x_4y_4z_4$ about the y_4 by angle γ_2 to obtain frame $x_5y_5z_5$. All frames are shown in Fig. 2.

The kinematic model of the Sphere will be derived in the assumption that the sphere rolls without slipping on the floor. To obtain it ignore the inner mechanism and only consider the driving mass if the mass rotates about imaginary horizontal axis by angle β, it causes the sphere rotates β in enough time too. So if the mass velocity be V_m then the sphere velocity is $(R/d)V_m$. Where R is sphere radius and d is the distance of driving mass to center of sphere.

So we freeze the sphere and calculate the velocity of the driving mass by moving the inner mechanism:

$$V_m = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} \dot{\gamma}_1 \\ \dot{\gamma}_2 \end{bmatrix} \tag{1}$$

$$a_{11} = \cos(\alpha)\cos(\theta)\sin(\gamma_2)\big(\cos(\phi)\sin(\gamma_1)+\sin(\phi)\cos(\gamma_1)\big) - \sin(\alpha)\sin(\gamma_2)\big(\sin(\phi)\sin(\gamma_1)-\cos(\phi)\cos(\gamma_1)\big)$$

$$a_{12} = \cos(\alpha)\cos(\theta)\cos(\gamma_2)\big(\sin(\phi)\sin(\gamma_1)-\cos(\phi)\cos(\gamma_1)\big) + \cos(\alpha)\sin(\theta)\sin(\gamma_2) + \sin(\alpha)\cos(\gamma_2)\big(\sin(\phi)\cos(\gamma_1)-\cos(\phi)\sin(\gamma_1)\big)$$

$$a_{12} = \sin(\alpha)\cos(\theta)\sin(\gamma_2)\big(\cos(\phi)\sin(\gamma_1)+\sin(\phi)\cos(\gamma_1)\big) + \cos(\alpha)\sin(\gamma_2)\big(\sin(\phi)\sin(\gamma_1)-\cos(\phi)\cos(\gamma_1)\big)$$

$$a_{22} = \sin(\alpha)\cos(\theta)\cos(\gamma_2)\big(\cos(\phi)\cos(\gamma_1)+\sin(\phi)\sin(\gamma_1)\big) - \sin(\alpha)\sin(\theta)\sin(\gamma_2) + \cos(\alpha)\cos(\gamma_2)\big(\sin(\phi)\cos(\gamma_1)+\cos(\phi)\sin(\gamma_1)\big)$$

And we have:

$$\begin{bmatrix} \dot{x}_s \\ \dot{y}_s \end{bmatrix} = \frac{R}{d} V_m \tag{2}$$

$$\omega_x = -\frac{\dot{y}_s}{R},\ \omega_y = \frac{\dot{x}_s}{R}, \omega_z = -\frac{[\vec{d} \times (m_m V_m)].[0\ 0\ 1]}{I_{zz}} \tag{3}$$

To obtain $\dot{\alpha}$, $\dot{\theta}$ and $\dot{\phi}$ we have:

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \dot{\alpha} \end{bmatrix} + R_z^{\alpha} \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} + R_z^{\alpha} R_{y_1}^{\theta} \begin{bmatrix} 0 \\ 0 \\ \dot{\phi} \end{bmatrix} \tag{4}$$

By solving eq.(4) for $\dot{\alpha}$, $\dot{\theta}$ and $\dot{\phi}$ yields:

$$\dot{\alpha} = \frac{\cos(\theta)\cos(\alpha)\omega_x + \cos(\theta)\sin(\alpha)\omega_y - \sin(\theta)\omega_z}{\sin(\theta)} \tag{5}$$

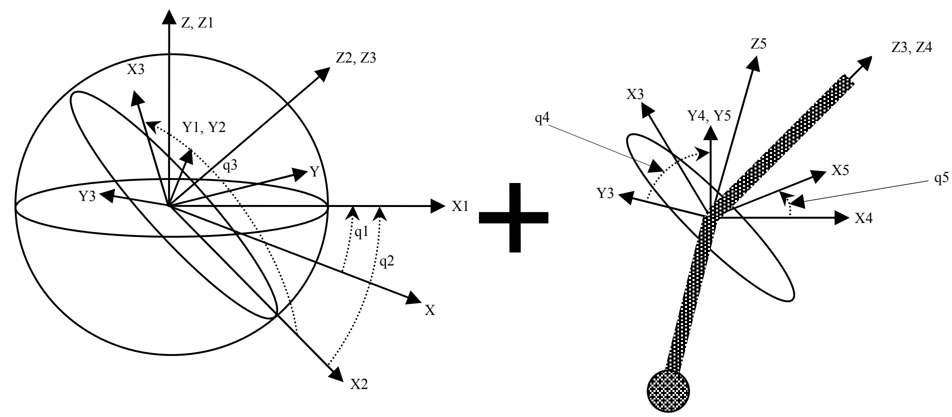

Fig.2 Configuration of sphere and inner mechanism.

$$\dot{\theta} = \frac{\cos(\alpha)\omega_x + \sin(\alpha)\omega_y}{\sin(\theta)} \tag{6}$$

$$\dot{\phi} = -\sin(\alpha)\omega_x + \cos(\alpha)\omega_y \tag{7}$$

Where:

$\dot{x}_s, \dot{y}_s$: Sphere velocity in x and y direction respectively.

ω_ξ : Angular velocity about ξ axis.

m_m : driving mass.

I_{zz} : Sphere and mechanism moment of inertia about vertical axis passing through sphere center.

R_ξ^β : Rotation matrix about ξ axis by angle β .

By substituting eqs.(1)-(3) in eqs.(5)-(7) lead to the kinematic model of the spherical mobile robot.

3 Dynamic model

In this section the dynamic equations for the Spherical robot are derived via applying the kane approach in quasi coordinates. The dynamic model is necessary for modeling the robots behavior and having a good knowledge of its motion properties. Since the robot has its own inertia, it will not respond instantly to velocity commands.

We define generalized speed and coordinate as:

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \end{bmatrix} = \begin{bmatrix} \alpha \\ \theta \\ \phi \\ \gamma_1 \\ \gamma_2 \end{bmatrix}, \qquad u_i = \dot{q}_i, \quad for \ \ i = 1 \ldots 5 \tag{8}$$

Kane's dynamic equations can be represented as:

$$F_r^* + F_r = 0, \quad 1 \le r \le p \tag{9}$$

$$F_r = \sum_{i=1}^{\lambda} \vec{V}_r^i . \vec{R}^i + \sum_{j=1}^{\gamma} \vec{\omega}_r^i . \vec{M}^j \tag{10}$$

$$F_r^* = \sum_{i=1}^{N} (\vec{V}_r^{p_i} . \tilde{\vec{R}}^i + \vec{\omega}_r^{p_i} . \tilde{\vec{M}}^i) \tag{11}$$

Where F_r is generalized active/external force F_r^* is generalized inertia force. Also, $\vec{R}^i$ and $\vec{M}^j$ are active force and active torque while $\tilde{R}^i$ and $\tilde{M}^i$ are inertial force and inertial torque; note that p_k is the k^{th} particle of system, $\vec{V}_r^{p_i}$ and $\vec{\omega}_r^{p_i}$ are partial linear velocity and partial angular velocity of particle p_i ; $\vec{V}_r^i$ and $\vec{\omega}_r^i$ are partial linear velocity and partial angular velocity of active force and torque contact points; N is the number of particles and λ and γ are the number of active force and active torque respectively.

The linear velocity, linear acceleration, angular velocity and angular acceleration of sphere and driving mass can be expressed as:

$$\begin{aligned} &\vec{\omega}_s = \dot{\alpha}\,\vec{k}_1 + \dot{\theta}\,\vec{j}_2 + \dot{\phi}\,\vec{k}_3 \\ &\vec{\alpha}_s = \ddot{\alpha}\,\vec{k}_1 + \ddot{\theta}\,\vec{j}_2 + \ddot{\phi}\,\vec{k}_3 + \dot{\alpha}\,\vec{k}_1 \times \dot{\theta}\,\vec{j}_2 + (\dot{\alpha}\,\vec{k}_1 + \dot{\theta}\,\vec{j}_2) \times \dot{\phi}\,\vec{k}_3 \\ &\vec{V}_s = \vec{\omega}_s \times (R\,\vec{k}_1), \qquad \vec{a}_s = \vec{\alpha}_s \times (R\,\vec{k}_1) \end{aligned} \tag{12}$$

$$\begin{aligned} &\vec{\omega}_m = \vec{\omega}_s + \dot{\gamma}_1\,\vec{k}_4 + \dot{\gamma}_2\,\vec{j}_5 \\ &\vec{\alpha}_m = \vec{\alpha}_s + \ddot{\gamma}_1\,\vec{k}_4 + \ddot{\gamma}_2\,\vec{j}_5 + \vec{\omega}_s \times \dot{\gamma}_1\,\vec{k}_4 + (\vec{\omega}_s + \dot{\gamma}_1\,\vec{k}_4) \times \dot{\gamma}_2\,\vec{j}_5 \\ &\vec{V}_m = \vec{V}_s + \vec{\omega}_m \times (-d\,\vec{k}_5), \qquad \vec{a}_m = \vec{a}_s + \vec{\alpha}_m \times (-d\,\vec{k}_5) \end{aligned} \tag{13}$$

Where (i_n, j_n, k_n) denote the unit vectors of $x_n y_n z_n$ coordinate which are described in the previous section. Note that the only active forces are the inner mass gravitational force and the rotor torques. Using the partial velocities, the generalized active forces for the five generalized speeds can be expressed as:

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \end{bmatrix} = -m_m g d \begin{bmatrix} 0 \\ sq_2 cq_5 + cq_2 sq_5 (cq_3 cq_4 - sq_3 sq_4) \\ -sq_2 sq_5 (cq_3 sq_4 + cq_4 sq_3) \\ -sq_2 sq_5 (cq_3 sq_4 + cq_4 sq_3) \\ cq_2 sq_5 + sq_2 cq_5 (cq_3 cq_4 - sq_3 sq_4) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \tau_1 \\ \tau_2 \end{bmatrix} \quad (14)$$

To determine the generalized inertial forces corresponding to the generalized speeds, the inertial force, $\tilde{R}^i$, and the inertia torque, $\tilde{M}^i$ are first derived in terms of the mass, M, the central inertial dyadic, I, the linear and angular accelerations, a and α, and the angular velocity, ω, of the centre of mass.

$$\begin{aligned} \tilde{\vec{R}}^i &= -m_i \vec{a}^i \\ \tilde{\vec{M}}^i &= -(I^i \vec{\alpha}^i + \vec{\omega}^i \times I^i \vec{\omega}^i) \end{aligned} \quad (15)$$

The nonholonomic constraints for the system are:

$$\begin{aligned} V_{sx} &= \left(\cos(q_1)u_2 + \sin(q_1)\sin(q_2)u_3\right)R \\ V_{sy} &= \left(\sin(q_1)u_2 - \cos(q_1)\sin(q_2)u_3\right)R \end{aligned} \quad (16)$$

By substituting eq.(14) and eq.(15) in eqs.(9)-(11) the dynamic model of the spherical mobile robot will be derived. Although the dynamic model can be derived via the Lagrange method simply, it will make the equations of motion too complicated. So, the Kane's method is used in this paper.

4 Control

4.1 PI Controller

The problem with the control the proposed robot is that it is impossible to control the proposed robot in high acceleration or dynamic mode. Regarding the fact that a sphere has 3 degrees of freedom based on its velocity, if we define the degrees of freedom as the rotation about the fixed coordinates axes, xyz, it will be sufficient to control the rotation about x and y axes to track the desired path. In this way, the rotation about the z axis will not play any role in displacement of the sphere and will cause the sphere to rotate around itself. However, this rotation will also be made by the inner mechanism motion. It must be noted that if the desired path had been designed in a way that causes the sphere turns around itself for a long time with an increasing or decreasing acceleration, the angular velocity of the sphere will be increased abnormally and the system turns into instability.

In order to solve the proposed problem, the sphere must be controlled by using the relations derived in the section 2 in the quasi-static mode.

In order to control the sphere, two separate controllers are needed: kinematic controller and dynamic controller. The kinematic controller will provide the desired inputs, $\dot{\gamma}_1$ and $\dot{\gamma}_2$, for the dynamic controller, while the dynamic controller generates the required torques for the dynamic model Fig. 3.

In order to calculate $\dot{\gamma}_1$ and $\dot{\gamma}_2$, by regards of $\dot{x}_d$ and $\dot{y}_d$, the eq.(1) can be used. However, the $\dot{x}_d + k_{x1}(\dot{x}_d - \dot{x}) + k_{x2}(x_d - x)$ & $\dot{y}_d + k_{y1}(\dot{y}_d - \dot{y}) + k_{y2}(y_d - y)$ terms will be used instead of the desired values of velocity.

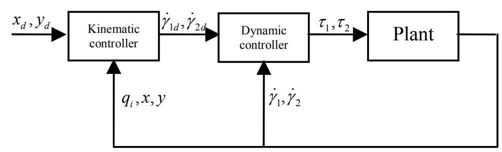

Fig.3 Controllers arrangement.

The added terms will correct the sphere position and velocity, especially after singular points. Hence:

$$\begin{bmatrix} \dot{\gamma}_1 \\ \dot{\gamma}_2 \end{bmatrix} = \frac{d}{R} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}^{-1} \begin{bmatrix} \dot{x}_d + k_{x1}(\dot{x}_d - \dot{x}) + k_{x2}(x_d - x) \\ \dot{y}_d + k_{y1}(\dot{y}_d - \dot{y}) + k_{y2}(y_d - y) \end{bmatrix} \quad (17)$$

So, the important point is to specify the singular points or the points in which $a_{11}a_{22} - a_{12}a_{21}$ will vanish. In order to specify these points we have:

$$a_{11}a_{22} - a_{12}a_{21} = 0 \rightarrow \begin{cases} \sin(\gamma_2) = 0 \\ \tan(\theta)\tan(\gamma_2)\cos(\phi + \gamma_1) = -1 \end{cases} \quad (18)$$

Hence, the singular points of the robot include two sets; the first set contains the points in which two arms of the robot aligned in the same direction and the inner mechanism can be moved in just one direction while in the second set the second arm will be parallel to the horizontal plane. In this situation, although the mechanism can be moved in two directions, these movements have just one projection in a horizontal plane.

It is possible for the robot to experience the singularity of the first set in its regular motion. The only solution for this problem is to provide an upper limit for the torques generated by the rotors.

Regarding the fact when using low acceleration the second link of the robot will never be parallel to the horizontal plane and will always deviate a little from the vertical situation, the singular points will not be experienced during these accelerations. The result of simulation is shown in Fig.4.

$m_s = 50\,kg, m = 30\,kg, R = 1\,m, d = .8\,m, I_s^{ii} = 25\,kgm^2, I_m^{ii} = 10\,kgm^2,$.

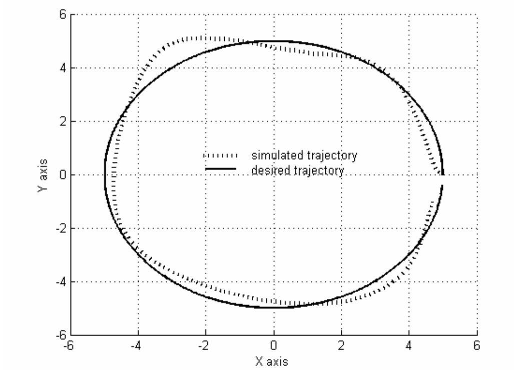

Fig.4 PI controller simulation result.

4.2 Fuzzy Controller

In this section, a fuzzy controller is used whose laws are determined via look up table method. The main object of the fuzzy controller is to identify the robot geometry and behavior in a better way. Hence, the problem kinematic will be rederived. It is known that if the rotor torques are vanished, the second linkage of the robot with inner mass will be aligned in the vertical direction. In this way, its direction will be passed through the point of contact between the sphere and the surface.

If inner mass position regarding to the fixed coordinate is expressed as:

$$\begin{bmatrix} x_m & y_m & z_m \end{bmatrix}^T = R_z^{\alpha} R_{y_1}^{\theta} R_{z_2}^{\phi} R_{z_3}^{\gamma_1} R_{y_4}^{\gamma_2} \begin{bmatrix} 0 & 0 & -d \end{bmatrix}^T \qquad (19)$$

And the second linkage is aligned vertically, the below relations are valid between rotation matrices;

$$R_{y_1}^{\theta} = (R_{y_4}^{\gamma_2})^{-1}, \qquad R_{z_2}^{\phi} = (R_{z_3}^{\gamma_1})^{-1} \qquad (20)$$

In other words, we have:

$$\theta = -\gamma_2, \qquad \phi = -\gamma_1, \qquad (21)$$

So, the inner mechanism will only rotate around vertical axis.

$$\begin{bmatrix} x_m & y_m & z_m \end{bmatrix}^T = R_z^{\alpha} \begin{bmatrix} 0 & 0 & -d \end{bmatrix}^T \qquad (22)$$

Now, by substituting eq.(21) in kinematic relations expressed in section 2, we have;

$$\begin{aligned} \dot{x}_s &= R(\sin(\alpha)\sin(\gamma_2)\dot{\gamma}_1 - \cos(\alpha)\dot{\gamma}_2) \\ \dot{y}_s &= -R(\cos(\alpha)\sin(\gamma_2)\dot{\gamma}_1 + \sin(\alpha)\dot{\gamma}_2) \end{aligned} \qquad (23)$$

$$\begin{aligned} \dot{\alpha} &= \cos(\gamma_2)\dot{\gamma}_1 \\ \dot{\theta} &= -\dot{\gamma}_2 \\ \dot{\phi} &= -\dot{\gamma}_1 \end{aligned} \qquad (24)$$

And Substituting $\dot{\gamma}_2 = 0$ in eq.(23) and integrating, we have:

$$\begin{cases} x_s = -R\cos(\alpha)\tan(\gamma_2) \\ y_s = -R\sin(\alpha)\tan(\gamma_2) \end{cases} \Rightarrow x_s^2 + y_s^2 = R^2\tan^2(\gamma_2) \qquad (25)$$

In this situation, the sphere has a circular motion path. In must be noted that by substituting $\dot{\gamma}_1 = 0$ in eq.(23) and integrating, we have($\alpha = cte$):

$$\begin{cases} x_s = -R\cos(\alpha)\gamma_2 \\ y_s = -R\sin(\alpha)\gamma_2 \end{cases} \Rightarrow y_s = kx_s \qquad (26)$$

That is a linear motion path and it is normal to initial circular path. Using these two mutually vertical motions, the sphere is able to approach any desired position. The sphere motion regarding to the variant values of α is illustrated in Fig. 5. Regarding the Fig. 5, the positive torque of the rotors will cause the robot to move in –x and +y directions. Hence, it is possible to approach the sphere to the specified direction by the value and sign of the torques.

$$\alpha = -\pi \;\rightarrow\; \begin{cases} \tau_1 \rightarrow -y \\ \tau_2 \rightarrow +x \end{cases}$$

$$\alpha = -\frac{\pi}{2} \;\rightarrow\; \begin{cases} \tau_1 \rightarrow +x \\ \tau_2 \rightarrow +y \end{cases}$$

$$\alpha = 0 \;\rightarrow\; \begin{cases} \tau_1 \rightarrow +y \\ \tau_2 \rightarrow -x \end{cases}$$

$$\alpha = \frac{\pi}{2} \;\rightarrow\; \begin{cases} \tau_1 \rightarrow -x \\ \tau_2 \rightarrow -y \end{cases}$$

$$\alpha = \pi \;\rightarrow\; \begin{cases} \tau_1 \rightarrow -y \\ \tau_2 \rightarrow +x \end{cases}$$

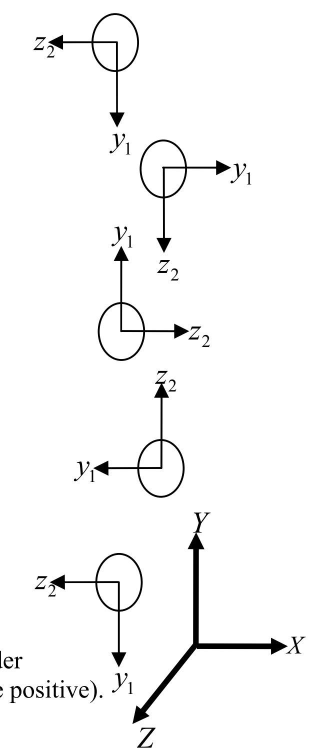

Fig.5 motion of sphere under α variation (τ_1, τ_2 and θ are positive).

In order to design the control law, two separate parallel controllers are proposed which tunes the motion in x and y direction, respectively. Each of these controllers has $3\times3\times5$ rules whose membership functions are shown in Fig.6. e_i is error in i direction.

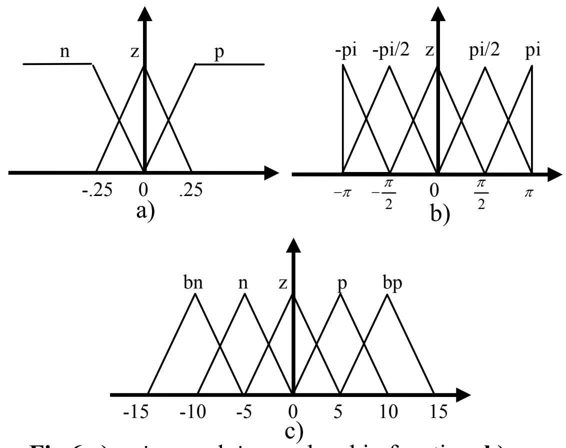

Fig.6 a) $e_x, \dot{e}_x, e_y$ and $\dot{e}_y$ membership function, **b)** α membership function, **c)** τ_1 and τ_2 membership function.

$m_s = 50\,kg, m = 30\,kg, R = 1\,m, d = .8\,m, I_s^{ii} = 25\,kgm^2, I_m^{ii} = 10\,kgm^2,$

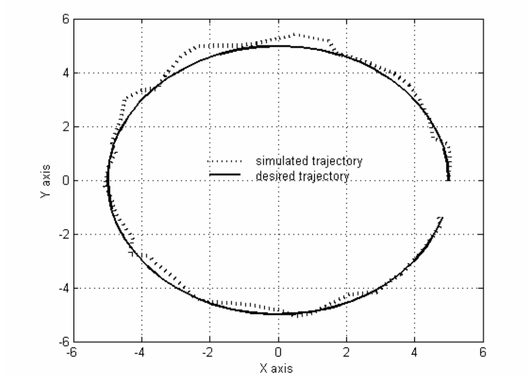

Fig.7 Fuzzy controller simulation result.

As an example, consider the case that alfa is vanished. So, the membership function for x direction can be expressed as;

If (e_x *is p and* $\dot{e}_x$ *is p and* α *is z) then (* τ_1 *is z and* τ_2 *is bp)*
If (e_x *is p and* $\dot{e}_x$ *is z and* α *is z) then (* τ_1 *is z and* τ_2 *is p)*
If (e_x *is p and* $\dot{e}_x$ *is n and* α *is z) then (* τ_1 *is z and* τ_2 *is z)*
If (e_x *is z and* $\dot{e}_x$ *is p and* α *is z) then (* τ_1 *is z and* τ_2 *is p)*
If (e_x *is z and* $\dot{e}_x$ *is z and* α *is z) then (* τ_1 *is z and* τ_2 *is z)*
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If (e_x *is n and* $\dot{e}_x$ *is p and* α *is z) then (* τ_1 *is z and* τ_2 *is z)*
If (e_x *is n and* $\dot{e}_x$ *is z and* α *is z) then (* τ_1 *is z and* τ_2 *is n)*
If (e_x *is n and* $\dot{e}_x$ *is n and* α *is z) then (* τ_1 *is z and* τ_2 *is bn)*

It must be noted that since the effect of θ will be neutralized by the γ_2, θ will affect the rotor aligning and so the sphere motion.

In order to simply the rules, this effect is limited to the sign of θ. In other words, whenever θ has a negative value, the first rotor desired torque will be changed sign.

The result of simulation is shown in Fig.7.

5 Conclusion

This paper presents a different mobile robot class that can achieve many kinds of unique motion, such as all direction driving and motion on rough ground. The motion properties of spherical mobile robot were analysed and the kinematic and dynamic model of robot derived. Finally a PI and fuzzy controller are proposed separately and their deal with this problem is compared. The effectiveness of the proposed method is shown via simulation.

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