Design and Development of a Spherical Robot (SpheRobot)

Deepak Pokhrel, Nutan Raj Luitel, Sukanta Das
Department of Mechanical Engineering
EIILM University
Malabassey, West Sikkim – 737121
{2064.deep, luitelnutanraj}@gmail.com,
sukanta.das@eiilmuniversity.ac.in

Dip Narayan Ray
Surface Robotics Laboratory
CSIR – Central Mechanical Engg. Research Institute
Durgapur 713209, India
dipnarayan.ray@gmail.com

***Abstract*— The research on mobile robots has been started in the last century and still advancements in different domains, such as locomotion principles, mechanism, control, sensing etc. are going on. Mobile robots use rolling, walking, flying, hopping, swimming, as means of locomotion. To implement these locomotions, apart from the actuators (i.e. motors, thrusters), limbs (wheels, legs, fins) have to be associated to generate the motion. Only in case of rolling, limbless locomotion is being used. Rolling can only be generated by rotation of a sphere. This has been used for the development of Spherical Mobile Robots. Obviously the other control and sensing accessories, power supply are to be confined within the sphere. Spherical Mobile Robots have the strong advantage of their shape offering rigidity, robustness, non-invertible, travel over rough surfaces and ease of locomotion. This paper deals with the design and development of a spherical robot (termed as 'SpheRobot') using the principle of inverted pendulum. The work has been supported by approximate mathematical modeling, analysis and experimentation. A wireless camera has been mounted on a Gimbal system inside the SpheRobot. The images are transmitted to the command station for monitoring. Presently the robot is being controlled remotely. Work is in progress to introduce autonomous mode with the help of non-contact type sensors.**

Keywords—mobile robot, spherical robot, pendulum

I. INTRODUCTION

Robotics [1] is the branch of technology that deals with the design, construction, operation and application of robots and computer systems for their control, sensory feedback, and information processing. These technologies deal with automated machines that can take the place of humans, in hazardous areas or manufacturing processes, or simply just resemble humans. Many of today's robots are inspired by nature contributing to the field of bio-inspired robotics [2].

Spherical robot may be the most preferred design due to its easy maneuverability, holonomic nature, omnidirectional movement. As a result the robot can navigate around any object easily and the chance of getting stuck in corners is reduced. Due to its shape there is no question of overturning as often found in case of traditional wheeled robots. This feature also allows them to be thrown or dropped. The stairs and ledges can also be overcome at ease which is not easy for wheeled or tracked mobile robots. Another major advantage of spherical robot is that being completely sealed, they are ideal for hazardous environments. This enables the robot for operation in snow, mud and if sealed properly, even in water also.

These advantages indicate that a spherical robot would be appropriate for many different mobile robotics applications such as surveillance, reconnaissance, hazardous environment assessment, search and rescue, as well as planetary exploration. Though a large number of concept models have been developed as a result of the research in the field of spherical robot, only a few have been very successful in practice. The current research work has attempted to develop indigenously a real- time low-cost spherical robot. All the components are available in Indian market at very low price. Unlike other spherical robots using pendulum mechanism, SpheRobot can take turn at any angle, certainly along an arc.

This paper is organized as follows: after this introduction, there is a literature survey. Section III describes the proposed design along with the technical specifications. Kinematic and dynamic modelings have been presented in section IV and V respectively. The modeling has been validated through simulation. Finally there are experiment, results, discussion and conclusion.

II. RELATED WORKS

The research on spherical robot has been started in 1996 through the work of Halme et al. [3]. There after different propulsion mechanisms have been devised. These include internal car based models, two independent rotating hemispheres, pendulum mechanism, relocation of centre of gravity, wind power, self deformation. The first spherical mobile robot was developed by Halme et al. The propulsion was derived from a wheel in contact with the bottom of the sphere and above the wheel was Inside Drive Unit (IDU) with power and communications. On the opposite end of the powered wheel is another stabilizing wheel. By steering the powered wheel, the sphere has the ability to turn. In 1997, Bicchi et al. proposed a design that was propelled by a small car resting at the bottom of the sphere [4]. The car could be steered to change the direction of the sphere. Similar design has been adopted in Israel to develop a robot called Spherical Autonomic Robot (SAR) [5]. Aalto University (formerly Helsinki University of Technology) has also used the internal car system but along with sprung central member mechanisms for their spherical robot called Rollo robot [6]. But finally they are using a pendulum mechanism for the third prototype of Rollo. The main disadvantages of car based propulsion mechanism are that motion is not instantaneous; collision can cause lose of contact or even flip over of the car; precise motion may not be possible due to internal slippage.

S. Bhattacharya has developed a design that involved a set of two mutually perpendicular rotors attached to the inside of a sphere [7]. The sphere is assembled in two halves, with each half containing a motor and rotor. The motors are mounted low, and by adjusting their speeds the motion is achieved. The robot can turn by slowing one motor, or even reversing one to spin on the vertical axis. However such design is not preferred due to complexity in the mechanical design and requirement of high performance motors. Another major drawback is that the internal components are not sealed due to the gap between the hemispheres.

The pendulum mechanism has been used by many researchers for its simplicity, easy to design nature. Cyclops, developed at Carnegie Mellon University, is a 5.5-inch diameter, 4.5- pound spherical robot intended for reconnaissance and surveillance in urban environments [8] using a pendulum mechanism. Similar pendulum mechanism has also been used in Groundbot developed by Rotundus [9]; Roball developed at the University of Sherbrook, Canada [10]; GIMBall developed by Aalto University [11]. However for this design rigidity of the main driving shaft and the high power of the driving motor are two important factors to be considered.

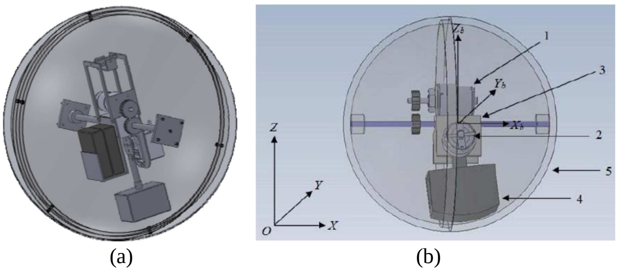
Propulsion can also be achieved by shifting the centre of gravity, either using single mass or multiple masses. R. Mukherjee et al. in their Spherobot design has proposed a central body with weights distributed radially along spokes fixed to the inside surface of the sphere [12]. The weights can actually be the pancake motors themselves, and move along the axes to change the center of mass. Another similar design has been proposed by A. Javadi and P. Mojabi, in their robot called August [13]. Spherobot was the first to realize the multiple-mass-shifting propulsion mechanism with a radial configuration, and the design was patented (U.S. Patent 6,289,263) [14]. A newer design for Spherobot was later introduced using three perpendicular and non-intersecting masses [15]. Lacks of precise control, instantaneous movement, efficiency are the hindrances of this design. The radial configuration of masses has the additional drawback of requirement of central hub, which limits the performance of the mechanism.

Alternate propulsion mechanisms, such as wind power or self deformation have been identified recently. Based on the concept of Jacques Blamont of the National Center for Space Studies in France (CNES) in the late 1970s, the University of Arizona has developed a “Mars Ball” concept, an inflatable 4 m by 5 m, 500 kg rover whose mobility was produced through sequenced inflation and deflation of air bags [16]. The self deformation is mostly achieved by using shape memory alloy (SMA).Y. Sugiyama [17] has proposed a design consists of a four rings attached in the center by shape memory alloy (SMA) wire. Using pulse width modulation, the SMA wire contracts in a certain order to make the sphere move. Ritsumeikan University in Japan has succeeded to develop a wheel and a sphere (called Koharo) with flexible outer structures and shape memory alloy (SMA) actuators [18]. A different type of deformable sphere is under development by iRobot in conjunction with the University of Chicago. Funded by the DARPA Chembots program, the iRobot Chembot is a soft, inflatable, silicone sphere that uses the principle of jamming to selectively control the rigidity of individual sectors of the sphere [19]. The hollow sphere is formed from triangular sections that are actually pouches of a fine powder [20]. These special types of spherical robots are still under research due to its low response time, complex structure and propulsion mechanism.

III. SPHEROBOT : THE PROPOSED DESIGN

The above study reveals that the pendulum-based drive system may be preferred to other driving mechanisms as the design is relatively simple and there are limited restrictions on how the shell must be made. The proposed model shown in Fig. 1(a) consists of three basic units; namely outer shell, inner drive unit and pendulum arrangement. In order to keep the mechanical design simple and powerful, gear drive has been used. There are two main motors driving the counter weight rotate about the horizontal axis and the vertical axis, as shown in Fig. 1(b). For simplicity, two motors are referred as motor 1(M1) and motor 2 (M2). M1 generates the driving torque about the vertical axis to make the sphere roll along the straight line and M2 generates the leaning torque about the horizontal axis to make the sphere to turn. The main concentration during the design phase was how to balance the masses about the axes so as to maintain the neutral equilibrium while the robot is not in motion. For the ease of manufacturing and assembly, it was decided to design the spherical shell into two halves. Initially the robot is controlled via remote controller manually. A wireless camera has been used for remote monitoring.

The mechanical structure of the Spherical Robot (SpheRobot) is shown in Fig.1 (a). SpheRobot consists of two motors, internal drive unit (IDU), a shaft, a counter-weight pendulum, and a shell. The shaft connected with the shell at two ends through a square plug and socket, serves as a frame to install other devices. The output shaft of M1 is fitted with a spur gear that meshes with another spur gear mounted on the main shaft. The dead weight of the pendulum is connected with the shaft of M2 by a link.



(a) (b)

Fig. 1. (a) 3D CAD view of the assembly (b) Different Body Parts: 1 – Driving motor, 2 – Steering motor, 3 - Internal Drive Unit (IDU), 4 - Counter weight pendulum, 5 - Shell

The principle of operation of SpheRobot is as follows. When M1 rotates around axis X_b and M2 is static, the rotation of the pendulum and the shaft around axis X_b changes the gravity center of the robot and produces a gravity torque that makes the robot move forward or backward. When both M1 and M2 rotate, the pendulum and the axle will tilt and produce a gravity torque to make the robot turn. As a consequence, driven by two motors, the spherical robot can move and turn as anticipated. Therefore the motion of the robot can be controlled by controlling these two motors [21].

TABLE I. TECHNICAL SPECIFICATION OF SPHEROBOT

Specifications	
Designation	Spherical robot (SpheRobot)
Dimension	Outside diameter – 320 mm Inside diameter – 300 mm
Weight	2.910 Kg (without dead weight)
Power	On-board 12V Li-Ion battery
Drive	DC Motor for driving and steering
Communication	RF communication for remote operation
Sensor	(presently) Wireless camera

As shown in Fig. 2, SpheRobot uses microcontroller based manual control for precise movement. A 2.4 GHz, 4-channel joystick has been used for transmitting four commands (forward, reverse, left and right turning) to the robot.

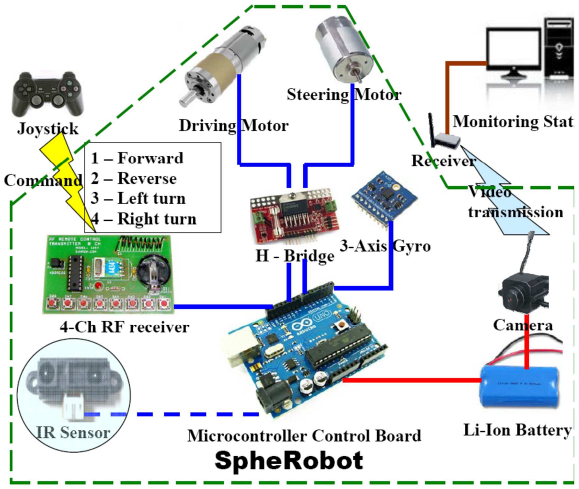


Fig. 2. The hardware architecture of the SpheRobot shows the precise control using Arduino and 3-Axis compass. The commands are sent manually using a 4 – channel joystick and the video is transmitted wirelessly to a remote computer. Work is in progress to introduce autonomous mode using IR sensor.

The motion of the robot is controlled by clockwise and anti-clockwise rotation of two different 12VDC geared motors for driving and steering. The decoded signal from the on-board receiver is fed to the Arduino microcontroller board for precise control. The 3-axis gyro is being employed for correcting the course of motion of the robot due to slippage, friction etc. For example, if the 'forward' command has been activated, then the change in only one direction (say along y-axis) is allowed. The change in other co-ordinates is stopped or constantly corrected to nullify the change from the motion information of the robot. The respective modified control signal is then sent to the driving and steering motors through an H-bridge. A small wireless camera has been installed on a Gimbal system and the video is transmitted to the monitoring station. The transmitted video is captured and saved automatically using a USB-based tuner card. The on-board power is supplied from a 12V rechargeable Li-Ion battery bank.

Most of the spherical robots developed earlier use manual mode of control. In the current research work, manual control has been implemented along with a provision for autonomous control. For autonomous control different obstacles need to be avoided for safe navigation. For this purpose an Infrared (IR) sensor can be used. The implementation of IR sensor is under progress.

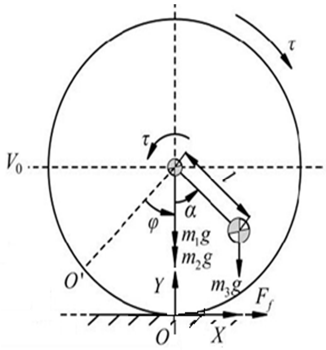


Fig. 3. Simplified model

IV. KINEMATIC MODELLING

For the purpose of analyzing the motion characteristics and the influence of the structural parameters, the model of SpheRobot is simplified to a multi body system composed up a rigid link and two equivalent point masses. The kinematics and dynamics model of SpheRobot is derived under the following assumptions:

1) The spherical robot moves following a straight line without any slippage
2) There is no frictional force/ slippage in the internal mechanism
3) The geometric center of the shell and the center of mass of the robot are concentric
4) The pendulum is considered as a point mass connected with a mass less rigid link
5) The spherical shell has no thickness and its mass is distributes uniformly

Nomenclature:

x_1,y_1	position of centre of mass w. r. t. the origin O, m
φ	spinning angle of the shell, rad ($0\leq \varphi \leq 2\pi$)
α	swinging angle of the counter-weight mass, rad
m_1	mass of the shell, Kg
m_2	mass of the inner drive unit, Kg
m_3	mass of the counter-weight mass, Kg
g	gravitational acceleration, m/s^2
R	radius of the spherical shell, m
l	length of the connecting rod, m
Ji	moment of inertia of the inner driver unit about

axis X_b, Kg.m^2

Js moment of inertia of the shell about the centre of spherical shell, Kg.m^2

T input torque of driving motor M1, N.m

The simplified model of SpheRobot is shown in Fig. 3. To describe the sphere and pendulum position, a two-dimension coordinate system is established. It is assumed that the coordinate of the mass center of the shell is (x_1, y_1) and the coordinate of the counter-weight is (x_2, y_2). From Fig. 3, the kinematics equations can be written as:

$$x_1 = R\varphi$$

$$y_1 = R$$

$$x_2 = l\,sin\alpha + R\varphi \quad (1)$$

$$y_2 = R - l\,cos\alpha \quad (2)$$

Differentiating equation (1) and (2), the velocity equations are obtained as

$$\dot{x}_2 = l\,cos\alpha.\dot{\alpha} + R\dot{\varphi} \quad (3)$$

$$\dot{y}_2 = l\,sin\alpha.\dot{\alpha} \quad (4)$$

Differentiating equation (3) and (4), the acceleration equations are obtained as

$$\ddot{x}_2 = l\,cos\,\alpha\,.\ddot{\alpha} - l\,sin\alpha.\dot{\alpha}^2 + R\ddot{\varphi} \quad (5)$$

$$\ddot{y}_2 = l\,cos\alpha.\dot{\alpha}^2 + l\,sin\alpha.\ddot{\alpha} \quad (6)$$

V. DYNAMIC MODELLING

The Lagrangian approach has been adopted to formulate the equations of motion of the robot because of its simplicity. Here a critical situation may happen; if M1 provides more torque than what is necessary to hold the counter-weight pendulum at a horizontal position, the pendulum will deviate from the horizontal position or even rotate full circles within the sphere. When this occurs, the robot is uncontrollable [21]. Here it is assumed that such critical situation will not occur [22].

Fig. 3 depicts a simplified planar model of SpheRobot, where the coordinate Σo{X, Y} is fixed to the ground; V_0 denotes the selected zero potential surface. The dynamic equations are derived by calculating the Lagrangian function L of this system, which is given as:

$$L = (T - P) \quad \text{(a)}$$

where T and P refer to the total kinetic energy and total potential energy of the system, respectively.

The kinetic energy of the system is computed as follows:

Kinetic energy generated by translational force of the system [23]

$(T_1) = \frac{1}{2}J_e\dot{\varphi}^2$ {for translational force, T= (1/2) mv^2} (7)

Now,

$$J_e = J_s + mR^2$$

Where m = total mass of shell, Kg = $m_1 + m_2 + m_3$

$$J_e = J_s + (m_1 + m_2 + m_3)R^2$$

The outer shell can be simplified as a thin wall spherical shell, so its central moment of inertia is $J_s = \frac{2}{3}m_1R^2$.

$$J_e = \left(\frac{5}{3}m_1 + m_2 + m_3\right)R^2$$

$$\text{T1} = \frac{1}{2}\left(\frac{5}{3}\text{m}_1 + \text{m}_2 + \text{m}_3\right)\text{R}^2\dot{\varphi}^2 \quad (8)$$

Kinetic energy generated by rotational force

$$\text{T2} = \frac{1}{2}\text{J}_\text{e}\dot{\alpha}^2 \quad (9)$$

Now,

$$\text{J}_\text{e} = \text{J}_\text{i} + \text{m}_3\text{l}^2$$

$$\text{T2} = \frac{1}{2}(\text{J}_\text{i} + \text{m}_3\text{l}^2)\,\dot{\alpha}^2 \quad (10)$$

Kinetic energy generated by centripetal force on the system

$$\text{T3} = -\text{m}_3\text{lR}\dot{\alpha}\dot{\varphi}\cos\alpha \quad (11)$$

Now total kinetic energy of the system

T = T1+T2+T3

$$\text{T} = \frac{1}{2}\left(\frac{5}{3}\text{m}_1 + \text{m}_2 + \text{m}_3\right)\text{R}^2\dot{\varphi}^2 + \frac{1}{2}(\text{J}_\text{i} + \text{m}_3\text{l}^2)\,\dot{\alpha}^2 - \text{m}_3\text{lR}\dot{\alpha}\dot{\varphi}\cos\alpha \quad (12)$$

The total potential energy of the system is the gravitational potential energy of the pendulum and is given as:

$$\text{P} = -\text{m}_3\text{gl}\cos\alpha \quad (13)$$

Putting the values of T and P from equations (12) and (13) in equation (a), we have

$$\text{L} = \frac{1}{2}\left(\frac{5}{3}\text{m}_1 + \text{m}_2 + \text{m}_3\right)\text{R}^2\dot{\varphi}^2 + \frac{1}{2}(\text{J}_\text{i} + \text{m}_3\text{l}^2)\,\dot{\alpha}^2 - \text{m}_3\text{lR}\dot{\alpha}\dot{\varphi}\cos\alpha + \text{m}_3\text{gl}\cos\alpha \quad (14)$$

Now to use the Lagrangian approach, an appropriate set of generalized coordinates, q_1 and q_2 were chosen which fully specify the system.

Taking the swing angle of the pendulum, α, and the rolling angle of the robot, φ, as two generalized coordinates.

$$q_1 = \varphi\,,\ q_2 = \alpha \quad (15)$$

From equations (14) and (15), we have

$$\text{L} = \frac{1}{2}\left(\frac{5}{3}\text{m}_1 + \text{m}_2 + \text{m}_3\right)\text{R}^2\dot{\text{q}}_1{}^2 + \frac{1}{2}(\text{J}_\text{i} + \text{m}_3\text{l}^2)\dot{\text{q}}_2{}^2 - \text{m}_3\text{lR}\dot{\text{q}}_2\dot{\text{q}}_1\cos\text{q}_2 + \text{m}_3\text{gl}\cos\text{q}_2 \quad (16)$$

It is important to note that the input torque τ of driving motor M1 works as an active inner force. By this notation, the Euler-Lagrange motion equations for the simplified system model are deduced as:

$$\frac{\text{d}}{\text{dt}}\left(\frac{\partial\text{L}}{\partial\dot{\text{q}}_1}\right) - \frac{\partial\text{L}}{\partial\text{q}_1} = -\tau$$

The direction of roll of robot is clockwise so negative sign of τ

$$\frac{\text{d}}{\text{dt}}\left(\frac{\partial\text{L}}{\partial\dot{\text{q}}_2}\right) - \frac{\partial\text{L}}{\partial\text{q}_2} = \tau$$

The direction of roll of pendulum is anti-clockwise so positive sign of τ

From above equations:

$$\frac{\text{d}}{\text{dt}}\left(\frac{\partial\text{L}}{\partial\dot{\text{q}}_1}\right) - \frac{\partial\text{L}}{\partial\text{q}_1} = \left(\frac{5}{3}\text{m}_1 + \text{m}_2 + \text{m}_3\right)\text{R}^2\ddot{\text{q}}_1 - \text{m}_3\text{lR}\cos\text{q}_2\,\ddot{\text{q}}_2 + \text{m}_3\text{lR}\sin\text{q}_2\,\dot{\text{q}}_2{}^2 - 0 = -\tau$$

(17)

Dividing both sides by R, the equation becomes

$$\left(\frac{5}{3}\text{m}_1 + \text{m}_2 + \text{m}_3\right)\text{R}\ddot{\text{q}}_1 - \text{m}_3\text{l}\cos\text{q}_2\,\ddot{\text{q}}_2 + \text{m}_3\text{l}\sin\text{q}_2\,\dot{\text{q}}_2{}^2 = -\left(\frac{1}{\text{R}}\right)\tau \quad (18)$$

$$\frac{\text{d}}{\text{dt}}\left(\frac{\partial\text{L}}{\partial\dot{\text{q}}_2}\right) - \frac{\partial\text{L}}{\partial\text{q}_2}$$

$$= (J_i + m_3 l^2)\ddot{q}_2 - m_3 lR\cos q_2\,\ddot{q}_1 + m_3 lR\sin q_2\,\dot{q}_1\dot{q}_2 - (m_3 lR\sin q_2\,\dot{q}_1\dot{q}_2 - m_3 gl\sin q_2) = \tau$$

Or, $(J_i + m_3 l^2)\ddot{q}_2$-$m_3 lR\cos q_2\,\ddot{q}_1 + m_3 gl\sin q_2 = \tau$ (19)

For the mathematical model, it is assumed that the sphere rolls on the ground without slipping. Under the pure rolling condition, we have

$$\dot{x} = \text{-}R\dot{\varphi} \quad (20)$$

Revising the generalized coordinate q1 = φ to be q1 = x

i.e. $\dot{x} = \dot{q}_1$ and since $\dot{\varphi} = \dot{q}_1$

Rearranging the terms, from equation (18) and (19)

$$\left(\frac{5}{3}m_1 + m_2 + m_3\right)\ddot{q}_1 + m_3 l\cos q_2\,\ddot{q}_2 - m_3 l\sin q_2\,\dot{q}_2{}^2 = \left(\frac{1}{R}\right)\tau \quad (21)$$

$$m_3 l\cos q_2\,\ddot{q}_1 + (J_i + m_3 l^2)\ddot{q}_2 + m_3 gl\sin q_2 = \tau \quad (22)$$

Equations (21) and (22) are the Euler-Lagrange equations of SpheRobot.

The dynamics equations of SpheRobot can be deduced in the matrix form as

$$M(q)\ddot{q} + C(q,\dot{q}) = B\tau \quad (23)$$

Where,

$$M = \text{Inertia Matrix} = \begin{pmatrix} \frac{5}{3}m_1 + m_2 + m_3 & m_3 l\cos q_2 \\ m_3 l\cos q_2 & j_i + m_3 l^2 \end{pmatrix},$$

$$C = \text{Non-linear terms} = \begin{pmatrix} \text{-}m_3 l\sin q_2\dot{q}_2{}^2 \\ m_3 gl\sin q_2 \end{pmatrix}, \boldsymbol{B} = \begin{pmatrix} 1/R \\ 1 \end{pmatrix}.$$

VI. SIMULATION

The simulation of the proposed model has been carried out using MATLAB. The coupled differential equations after solving the Lagrangian is first simplified and then solved in MATLAB in order to obtain different characteristics.

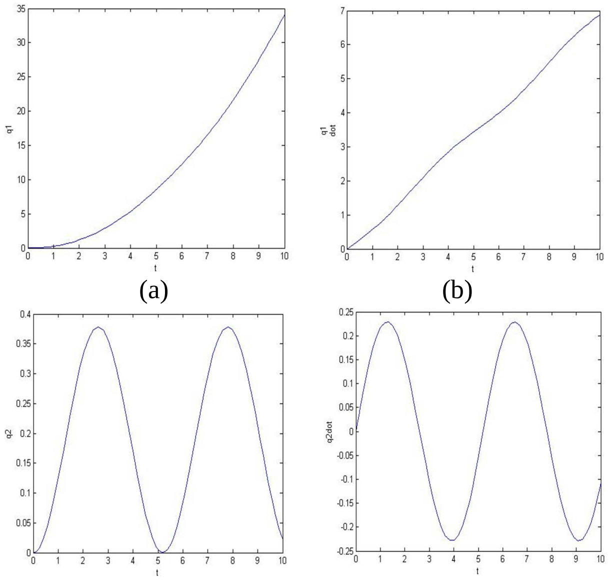
The coupled differential equations after solving the Lagrangian are given in equations (21) and (22).

After the simplification of equations (21) and (22), the simplified form becomes:

$$\frac{d^2q_1}{dt^2} = \frac{-\left(3\left(m_3^2 l^2\cos q_2 Rg\sin q_2 - m_3 l\cos q_2 R\tau + m_3 l\sin q_2\left(\frac{dq_2}{dt}\right)^2 RJ_i + m_3^2 l^3\sin q_2\left(\frac{dq_2}{dt}\right)^2 R + \tau J_i + \tau m_3 l^2\right)\right.}{(R(-5m_1J_i - 5m_1m_3l^2 - 3m_2J_i - 3m_2m_3l^2 - 3m_3J_i - 3m_3^2l^2 + 3m_3^2l^2\cos q_2^2))} \quad (24)$$

$$\frac{d^2q_2}{dt^2} = \frac{\left(3m_3^2l^2\cos q_2\sin q_2\left(\frac{dq_2}{dt}\right)^2 R + 3m_3 l\cos q_2\tau + 5m_3 gl\sin q_2 Rm_2 + 3m_3 gl\sin q_2 Rm_2 + m_3^2 gl\sin q_2 R - 5\tau Rm_1 - 3\tau Rm_2 - 3\tau Rm_3\right.}{(R(-5m_1J_i - 5m_1m_3l^2 - 3m_2J_i - 3m_2m_3l^2 - 3m_3J_i - 3m_3^2l^2 + 3m_3^2l^2\cos q_2^2} \quad (25)$$

Solution of differential equations (24) and (25) using MATLAB provides the following curves. Time is taken as 10 seconds and all initial conditions zero.



(a) (b)

(c) **(d)**

Fig. 4. Plot of the generalized co-ordinate systems and its derivative with reference to time (a) Spinning angle of the shell (q_1) vs. Time (t) graph (b) Spinning velocity of the shell ($\dot{q}_1$) vs. Time (t) graph (c) Swinging angle of the counter weight (q_2) vs. Time (t) graph (d) Swinging velocity of the counter weight ($\dot{q}_2$) vs. Time (t) graph

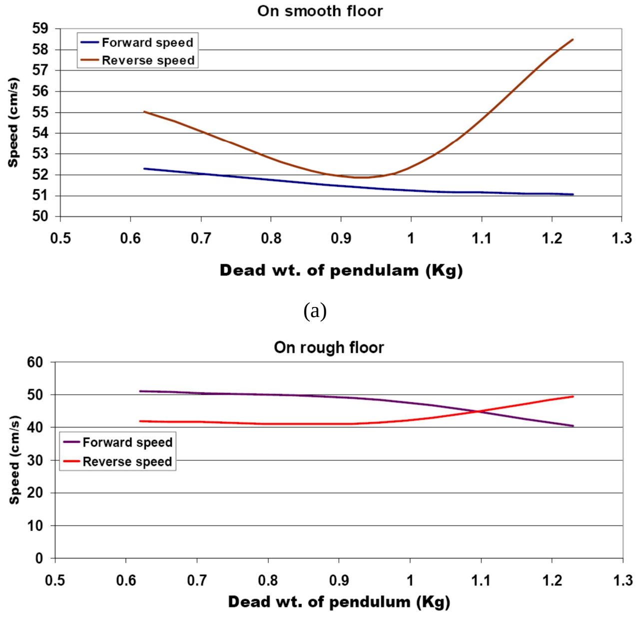
VII. EXPERIMENT, RESULT AND DISCUSSION

The robot uses the counter weight for its movement in all the four directions (forward, reverse, left and right). So changes in the value of the counter-weight will lead to different behaviour of motion of the robot. Sometimes it will increase the power at the cost of reduction of speed; sometime speed will increase with decrease in motive power. SpheRobot has been tested on different terrains to find out its maneuverability. The following figures (Fig. 5) depict the operation of the robot on smooth indoor floors, outdoor grassy land and rough concrete floor.

As mentioned the mobility of the robot depends not only on the counter-weight but also on the power of motor. However, it has been found that the obstacle overriding capability increases with the increase in counter-weight. Obviously this will decrease the speed of the robot. Due to difference in motor characteristics for clockwise and anticlockwise rotation, the forward and the reverse speeds on same terrain/ surface are also different. Following graphs in Fig. 6 demonstrate the variation of forward and reverse speeds of the robot on smooth floor (ceramic tiles) in indoor environment and rough surface in outdoor environment (semi-finished concrete).

(a) (b) (c)

Fig. 5. :The operation of SpheRobot in different terrains (a) indoor smooth floors (b) grassy land (c) rough concrete surface



(a)

(b)

Fig. 6. : Variation of forward and reverse speeds on (a) smooth floor (b) rough surface

Both the graphs show similar trends for forward speed variation with the change in counter-weight. With the increase in weight power requirement increases and hence the speed decreases. But in case of reverse motion the speed of the robot first decreases with increase in counter weight and then increases. Though attempt has been made to distribute the weights uniformly about both the axes, but it has been found the weight is slightly more in the side where battery is placed (due to heavier weight of the battery) and the reverse motion of the robot takes place when it moves in the direction of the battery. As a result this weight difference provides advantage to the forward motion and hindrance to the reverse motion.

VIII. CONCLUSION

This paper describes the design, modeling and experimentation of a mobile robot with a spherical shape. This robot was designed to act as a platform to carry wireless camera in an environment where the conditions are harsh or the stability of the mechanical platform is critical. Mobility is one of the important issues during the development of mobile robots for rough terrain, typically faced in outdoor missions or in space. Wheels, legs or their combinations are used by various types of mobile robots for locomotion. However, these kinds of systems require most efficient and versatile mechanisms of locomotion for working in rough and uneven terrains. Spherical mobile robot can achieve different kinds of unique motion, such as all-direction driving and motion on rough ground, without losing stability.

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