Technical Report

BB8 – Spherical Robot

Submitted in partial fulfillment of the requirements for the course of

ENPM662 – Introduction To Robot Modeling

by

Adheesh Chatterjee

UID – 116236935

M.Eng Robotics

PROJECT SUPERVISOR

Prof Chad Kessens

UNIVERSITY OF MARYLAND 1856

A. JAMES CLARK
SCHOOL OF ENGINEERING

TABLE OF CONTENTS

CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

A spherobot or a spherical robot is used to describe mobile “ball-like” robots that move along the ground by rolling about their outer spherical shell. They are generally comprised of an outer spherical shell and an internal propulsion mechanism. The shell may be made of multiple parts, but they all move and rotate together as a single body as the robot rolls.

While the mechanical design of the internal propulsion mechanism can vary greatly, the primary means of locomotion is by shifting the centre of mass of the sphere. The acceleration due to gravity acting on the centre of mass generates a torque on the sphere causing it to roll. By actively shifting the centre of mass inside, a spherical robot can be directed to travel in a controlled manner. The spherical shape of this class of mobile robot offers several advantages over other forms of surface-based locomotion like wheels, tracks, or legs.

1.2 MOTIVATION

Typical mobile robots generally face the issue of mobility. Wheels, legs or a combination of both are used by most mobile robots for locomotion. However, these kinds of robots require highly versatile and efficient mechanisms for locomotion for working in rough and uneven terrains. Spherobots can achieve different kinds of unique motions without losing stability, hence proving advantageous.

Fig. 1

- Spherical robots, due to their geometry, cannot overturn
- They do not have limbs which can get caught or hooked on certain obstacles.
- Theoretically, they are omnidirectional. In general, they can move in any direction on a plane surface, so it is easier to avoid obstacles or to find feasible routes.
- All devices in the robot are usually enclosed in a type of spherical shell, so they are protected from direct impacts and corrosion due to hazardous chemicals or environmental conditions
- The shell of the spherobot can provide a very high level of robustness with no major points of weakness, whereas wheels, tracks, or legs can be damaged, potentially disabling a robot’s ability to move.

With so many advantages, Spherobots have immense potential and applications in surveillance, reconnaissance, hazardous environment assessment, search and rescue, as well as planetary exploration and terrain mapping

CHPATER 2
MODEL DEVELOPMENT

2.1 POSSIBLE DESIGNS

Fig. 2

This mechanism uses a stool type set-up which allows to freely move a magnet around the upper part of the sphere. The drive system probably uses four omni wheels with ball bearings. Such configuration would allow to rotate the sphere in any direction.

The motorized arm has a spherical joint that allows it to flex in any direction. The head rotation motor is probably attached to the end of the mast. The head itself is probably very light and has magnetic rollers attached to the base. That would allow it to smoothly roll over the spherical body.

Fig. 3

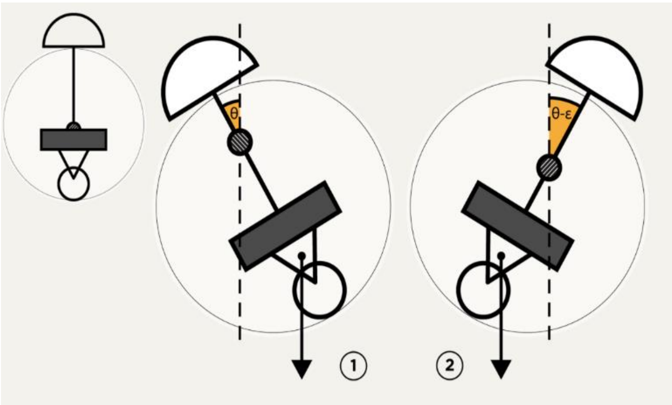

Fig. 4

The wheels are forced down against the wall of BB-8 by either springs or gravity. Rotating the wheels shifts the centre of the system's mass, off the vertical line that includes the centre of the ball and the contact point with the ground.

Leaning generates a moment which moves the base in the direction that the wheels were shifted to. If there were a mast mounted perpendicularly on top of the wheel base, the ball would move in a direction opposite to the mast.

The head is attached to the mast through the sphere magnetically as stated in the patent. This probably involves a set of attractive and repelling magnets. Repulsion probably keeps the head from contacting the ball, and magnetic attraction around the edges of the head keeps it from rolling off.

The BB8 slows the motors down and the head is allowed to roll forward. Once the head is pointing forward, the motors are resumed, and we get that nice full-tilt roll that's shown in the movies. Alternately, it's possible that the motors drive the mast forward, letting the ball move backwards, and then the motors maintain constant angle as BB-8 moves forward.

2.2 APPROACH

As part of my project, I will develop a spherobot specifically the BB-8 robot from the Star Wars movies and demonstrate its motion of rolling on a plane possibly traversing a highly descriptive and varied environment to prove its effectiveness.

As can be observed from the BB8 droid, the robot will move on the base shell which will have 3 DOF – The body will move forward and move sideways. The third DOF will be the body spinning on its axis to provide stability as, when and if required. This is achieved by the concept of Holonomy and Holonomic constraints.

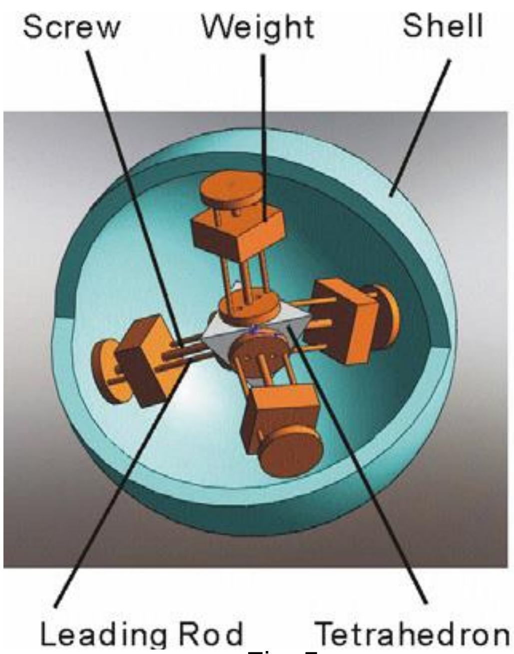

Fig. 5

The head of the robot which carries the wireless camera will move along the body in either forward or sideways direction. The third DOF would be the spinning of the head on its axis to enhance surveillance capabilities as, when and if required

The CAD Model of the shell of BB8 Droid is already completed. The Inner Design mechanism is complex, but a mathematical model has been developed on one of the possible design parameters.

The Velocity Kinematics and Dynamics of the internal mechanism of system have been developed to determine the orientation and locomotion of the robot. The movement of the internal mechanism causes the outer shell of the robot to move.

2.3 PROPOSED DESIGN AND DESCRIPTION

As discussed in Section 2.1 and 2.2, 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 consists of three basic units: namely 1) outer shell, 2) inner drive unit and 3) Pendulum Arrangement.

In order to keep the mechanical design simple and powerful, a gear drive can be used. There are two main motors driving the counter weight rotate about the horizontal axis and the vertical axis. 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 idea here is to maintain the balance between the masses about the axes so as to maintain the neutral equilibrium while the robot is not in motion.

The principle of operation of BB8 is proposed as follows. When M1 rotates around axis X and M2 is static, the rotation of the pendulum around axis X changes the gravity center of the robot and produces a gravity torque that makes the robot move forward or backward.

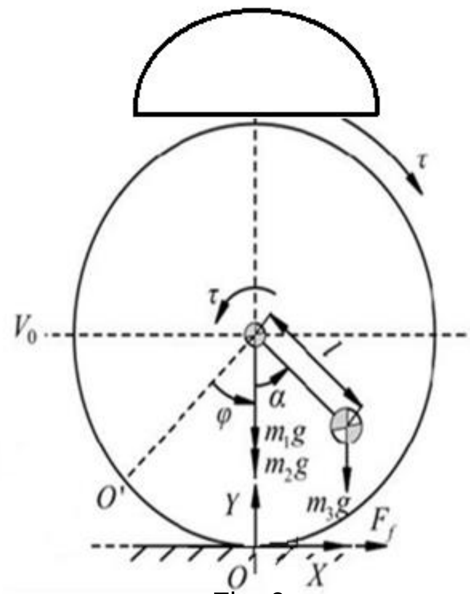

Fig. 6

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 required. Therefore, the motion of the robot can be controlled by controlling these two motors

In real time, it is necessary for the BB8 to carry out the turning and driving motions at the same time. Based on this fact, we separate the turning and driving motions apart, to solve nonholonomic problems.

With this decoupling method, the non-holonomic system changes into two decoupled holonomic subsystems. In other words, it is assumed that the dynamics of one DOF does not affect the dynamics of the other one. Therefore, the dynamic model of two subsystems can be written independently from each other.

The Euler angles are used to describe the relative angular motions of the rigid bodies constituting the entire system, i.e. the spherical shell and actuation mechanism.

The dynamic equations of motion are obtained through the Euler-Lagrange method.

2.4 ASSUMPTIONS

1) The spherical robot moves following a straight line on a perfectly horizontal surface without any slippage.
2) There is no frictional force/ slippage in the internal mechanism.
3) The geometric centre of the shell and the centre 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 distributed uniformly.
6) The pendulum mechanism has been decoupled using the decoupling principle.

7) The inner components are considered point masses concentrated to the centre of the ball.
8) The pendulum is in vertical downward position when the sphere is in static equilibrium

CHAPTER 3
MATHEMATICAL MODELING

Forward and turning motions of the rolling sphere are schematically represented in Fig. 7 and Fig. 8 respectively. System parameters are presented in Table 1.

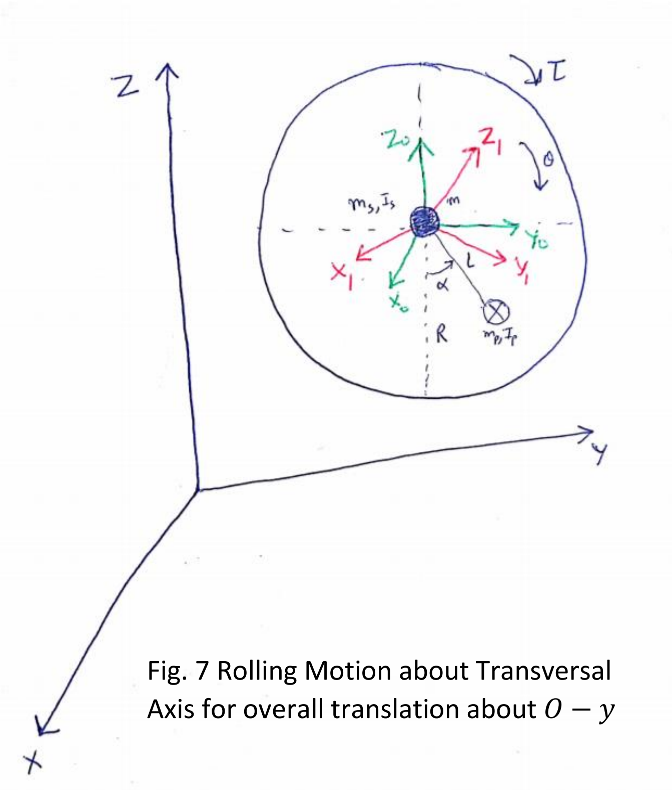

Fig. 7 Rolling Motion about Transversal Axis for overall translation about $O-y$

O_f	$O - xyz$
O_{f0}	$O - x_0y_0z_0$
O_{f1}	$O - x_1y_1z_1$
$O - x_1$	Transversal Axis
$O - y_1$	Longitudinal Axis
θ, ϕ, ψ	Rolling Angle of Sphere about x,y and z axes
α, β	DOF of Pendulum
R	Radius of Sphere
l	Length of Connecting Rod
g	Acceleration due to gravity
ω	Angular Velocity
m_s	Mass of Shell
m_p	Mass of Pendulum
I_s	Moment of Inertia of Shell
I_p	Moment of Inertia of Pendulum

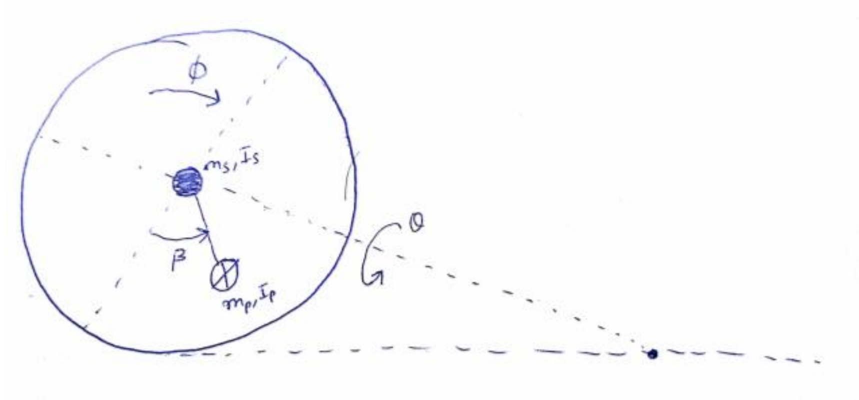

Fig. 8 Rolling Motion about Longitudinal Axis for overall translation about $O-x$

3.1 VELOCITY KINEMATICS

Since the sphere rotates around the transversal and longitudinal axes, the rotation matrices between O_{f0} and O_{f1} can be written as

$$R_{1X}^{0}(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta & sin\theta \\ 0 & -sin\theta & cos\theta \end{bmatrix} \qquad R_{1Y}^{0}(\phi) = \begin{bmatrix} cos\phi & 0 & -sin\phi \\ 0 & 1 & 0 \\ sin\phi & 0 & cos\phi \end{bmatrix}$$

Where R_{1X}^{0} is rotation about X and R_{1Y}^{0} is rotation about Y

The angular velocity ω^{s} and linear velocity v^{s} of the centre of the sphere can be given as

$$\omega_{x}^{s} = -\dot{\theta}\hat{\imath} \qquad \omega_{y}^{s} = -\dot{\phi}\hat{\jmath}$$

$$v_{x}^{s} = \omega_{x}^{s} \times r \qquad v_{y}^{s} = R\dot{\phi}\hat{\imath}$$
$$\Longrightarrow v_{x}^{s} = -\dot{\theta}\hat{\imath} \times -R\hat{k} \qquad \Longrightarrow v_{y}^{s} = -\dot{\phi}\hat{\jmath} \times -R\hat{k}$$
$$\Longrightarrow v_{x}^{s} = -R\dot{\theta}\hat{\jmath} \qquad \Longrightarrow v_{x}^{s} = R\dot{\phi}\hat{\imath}$$

where θ and ϕ represent rolling angle of the sphere around x and y axes and i and j are unit vectors on x and y axes.

The position vector r^{p1} is the position of the mass centre of the pendulum in O_{f1}

$$r_{x}^{p1} = \begin{bmatrix} 0 \\ lsin\alpha \\ -lcos\alpha \end{bmatrix} \qquad r_{y}^{p1} = \begin{bmatrix} -lsin\beta \\ 0 \\ -lcos\beta \end{bmatrix}$$

where α and β represent rotation of the pendulum around x and y axes and k is a unit vector on z axis

Now the position vector r^{p0} is the position of the mass centre of the pendulum in O_{f0}

$$r_{x}^{p0} = R_{1x}^{0}.r_{x}^{p1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta & sin\theta \\ 0 & -sin\theta & cos\theta \end{bmatrix} . \begin{bmatrix} 0 \\ lsin\alpha \\ -lcos\alpha \end{bmatrix} = \begin{bmatrix} 0 \\ lsin(\alpha - \theta) \\ -lcos(\alpha - \theta) \end{bmatrix}$$

$$r_{y}^{p0} = R_{1x}^{0}.r_{y}^{p1} = \begin{bmatrix} cos\phi & 0 & -sin\phi \\ 0 & 1 & 0 \\ sin\phi & 0 & cos\phi \end{bmatrix} . \begin{bmatrix} -lsin\beta \\ 0 \\ -lcos\beta \end{bmatrix} = \begin{bmatrix} -lsin(\beta - \phi) \\ 0 \\ -lcos(\beta - \phi) \end{bmatrix}$$

The position vector r^{p} of the mass centre of the pendulum in O_{f} is the same as r^{p0}

Angular Velocity

The angular velocity of the pendulum ω^{p1} is defined in O_{f1}

$$\omega_{x}^{p1} = \dot{\alpha}\hat{\imath} \qquad \omega_{y}^{p1} = \dot{\beta}\hat{\jmath}$$

Now, the angular velocity of the pendulum ω^{p0} is defined in O_{f0}

$$\omega_x^{p0} = \omega_x^s + R_{1\,x}^0 . \omega_x^{p1} = \begin{bmatrix} -\dot{\theta} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta & sin\theta \\ 0 & -sin\theta & cos\theta \end{bmatrix} . \begin{bmatrix} \dot{\alpha} \\ 0 \\ 0 \end{bmatrix} = (\dot{\alpha} - \dot{\theta})\hat{\imath}$$

$$\omega_y^{p0} = \omega_y^s + R_{1\,y}^0 . \omega_y^{p1} = \begin{bmatrix} 0 \\ -\dot{\phi} \\ 0 \end{bmatrix} + \begin{bmatrix} cos\phi & 0 & -sin\phi \\ 0 & 1 & 0 \\ sin\phi & 0 & cos\phi \end{bmatrix} . \begin{bmatrix} 0 \\ \dot{\beta} \\ 0 \end{bmatrix} = (\dot{\beta} - \dot{\phi})\hat{\jmath}$$

The angular velocity of the pendulum ω^p in O_f is the same as ω^{p0}

Linear Velocity

The linear velocity v^p of the mass centre of the pendulum in O_f

$$v_x^p = v_x^s + \omega_x^p \times r_x^p = \begin{bmatrix} 0 \\ -R\dot{\theta} \\ 0 \end{bmatrix} + \begin{bmatrix} \dot{\alpha} - \dot{\theta} \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ lsin\alpha \\ -lcos\alpha \end{bmatrix} = \begin{bmatrix} 0 \\ -R\dot{\theta} + (\dot{\alpha} - \dot{\theta})lcos(\alpha - \theta) \\ (\dot{\alpha} - \dot{\theta})lsin(\alpha - \theta) \end{bmatrix}$$

$$v_y^p = v_y^s + \omega_y^p \times r_y^p = \begin{bmatrix} R\dot{\phi} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{\beta} - \dot{\phi} \\ 0 \end{bmatrix} \times \begin{bmatrix} -lsin\beta \\ 0 \\ -lcos\beta \end{bmatrix} = \begin{bmatrix} R\dot{\phi} - (\dot{\beta} - \dot{\phi})\, lcos(\beta - \phi) \\ 0 \\ \left(\dot{\beta} - \dot{\phi}\right) lsin(\beta - \phi) \end{bmatrix}$$

3.2 DYNAMIC MODEL

The dynamical modeling equations of the rolling sphere are decoupled as mentioned in Section 2.3.

In this approach, the dynamic interaction between rotations of the sphere around the transversal and longitudinal axes is neglected. On the other hand, the rolling motion of the sphere is provided by the internal pendulum, which make the sphere rotate around the transversal and longitudinal axes. The rotational motion of the sphere around the vertical z axis is assumed to be negligible with respect to other rotations around the transversal and longitudinal axes.

$$L = KE - PE$$

The Kinetic Energy will depend on the translational force, the rotational force and the centripetal force.

$$KE = K_1 + K_2 + K_3$$

Where

$K_1 = \frac{1}{2} m_s v_s^2 + \frac{1}{2} m_p v_p^2$ is the KE due to translation force

$K_2 = \frac{1}{2} I_s \omega_s^2 + \frac{1}{2} I_p \omega_p^2$ is the KE due to rotation force

$K_3 = \frac{m_p v_p^2}{r_p}$ is the KE due to centripetal force

We also calculate

$I_s = \frac{2}{3}m_s R^2$ $\qquad$ $I_p = \frac{m_p l^2}{12} + m_p\left(\frac{l}{2}\right)^2$

The potential energy of the system will depend only on the pendulum

$$PE = m_p g r^{p*}$$

Where r^{p*} is the vertical component of the pendulum

By decoupling the system, the Lagrangian L can be split into L_x and L_y that include terms due to rotation only about the transversal and longitudinal axes

The Lagrangians are given by –

$$L_x = \frac{1}{2}m_s(v_x^s)^2 + \frac{1}{2}m_p(v_x^p)^2 + \frac{1}{2}I_s(\omega_x^s)^2 + \frac{1}{2}I_p(\omega_x^p)^2 + \frac{m_p(v_x^p)^2}{r_x^p} + m_p g r_x^{p*}$$

$$L_y = \frac{1}{2}m_s(v_y^s)^2 + \frac{1}{2}m_p(v_y^p)^2 + \frac{1}{2}I_s(\omega_y^s)^2 + \frac{1}{2}I_p(\omega_y^p)^2 + \frac{m_p(v_y^p)^2}{r_y^p} + m_p g r_y^{p*}$$

Substituting the values we get,

$$\begin{aligned}L_x = {} & \frac{1}{2}m_s(-R\dot{\theta})^2 + \frac{1}{2}m_p\left(\left(-R\dot{\theta} + \left(\dot{\alpha} - \dot{\theta}\right) lcos(\alpha - \theta)\right)^2 + \left(\left(\dot{\alpha} - \dot{\theta}\right) lsin(\alpha - \theta)\right)^2\right) \\ & + \frac{1}{2}\left(\frac{2}{3}m_s R^2\right)\left(-\dot{\theta}\right)^2 + \frac{1}{2}\left(\frac{m_p l^2}{12} + m_p\left(\frac{l}{2}\right)^2\right)\left(\dot{\alpha} - \dot{\theta}\right)^2 \\ & - \frac{m_p\left(\left(-R\dot{\theta} + \left(\dot{\alpha} - \dot{\theta}\right) lcos(\alpha - \theta)\right)^2 + \left(\left(\dot{\alpha} - \dot{\theta}\right) lsin(\alpha - \theta)\right)^2\right)}{l} \\ & - m_p glcos(\alpha - \theta)\end{aligned}$$

$$\begin{aligned}L_y = {} & \frac{1}{2}m_s(R\dot{\phi})^2 + \frac{1}{2}m_p\left(\left(R\dot{\phi} + \left(\dot{\beta} - \dot{\phi}\right) lcos(\beta - \phi)\right)^2 + \left(\left(\dot{\beta} - \dot{\phi}\right) lsin(\beta - \phi)\right)^2\right) \\ & + \frac{1}{2}\left(\frac{2}{3}m_s R^2\right)(-\dot{\phi})^2 + \frac{1}{2}\left(\frac{m_p l^2}{12} + m_p\left(\frac{l}{2}\right)^2\right)(\dot{\beta} - \dot{\phi})^2 \\ & - \frac{m_p\left(R\dot{\phi} + \left(\dot{\beta} - \dot{\phi}\right) lcos(\beta - \phi)\right)^2 + \left(\left(\dot{\beta} - \dot{\phi}\right) lsin(\beta - \phi)\right)^2}{l} \\ & - m_p glcos(\beta - \phi)\end{aligned}$$

The Euler-Lagrange equations of the system are written as follows –

For translation along $O-y$ direction,

$$\frac{d}{dt}\left(\frac{\partial L_x}{\partial q_i}\right)-\frac{\partial L_x}{\partial q_i}=Q_i$$

Where q_i are the joint variables and Q_i represents the input torque acting on the system.

$q=\begin{bmatrix}\theta\\ \alpha\end{bmatrix}$ and $Q=\begin{bmatrix}\tau_\theta\\ \tau_\alpha\end{bmatrix}$

For translation along $O-x$ direction,

$$\frac{d}{dt}\left(\frac{\partial L_y}{\partial q_i}\right)-\frac{\partial L_y}{\partial q_i}=Q_i$$

Where q_i are the joint variables and Q_i represents the input torque acting on the system.

$q=\begin{bmatrix}\phi\\ \beta\end{bmatrix}$ and $Q=\begin{bmatrix}\tau_\phi\\ \tau_\beta\end{bmatrix}$

So for $q=\begin{bmatrix}\theta\\ \alpha\\ \phi\\ \beta\end{bmatrix}$, the state space equation can be given by

$$M\big(q(t)\big)\ddot{q}(t)+V\big(q(t),\dot{q}(t)\big)=u(t)$$

$$\begin{bmatrix}M_{11} & M_{12} & M_{13} & M_{14}\\ M_{21} & M_{22} & M_{23} & M_{24}\\ M_{31} & M_{32} & M_{33} & M_{34}\\ M_{41} & M_{42} & M_{43} & M_{44}\end{bmatrix}\cdot\begin{bmatrix}\ddot{q_1}\\ \ddot{q_2}\\ \ddot{q_3}\\ \ddot{q_4}\end{bmatrix}+\begin{bmatrix}V_{11}\\ V_{21}\\ V_{31}\\ V_{41}\end{bmatrix}=\begin{bmatrix}\tau_\theta\\ \tau_\alpha\\ \tau_\phi\\ \tau_\beta\end{bmatrix}$$

$M_{11}=$ see MATLAB script

$M_{12}=$ see MATLAB script

$M_{13}=0$

$M_{14}=0$

$M_{21}=$ see MATLAB script

$M_{22}=$ see MATLAB script

$M_{23}=0$

$M_{24}=0$

$M_{31} = 0$

$M_{32} = 0$

$M_{33} =$ see MATLAB script

$M_{34} =$ see MATLAB script

$M_{41} = 0$

$M_{42} = 0$

$M_{43} =$ see MATLAB script

$M_{44} =$ see MATLAB script

Non-linear Matrix

$V_{11} =$ see MATLAB script

$V_{12} =$ see MATLAB script

$V_{13} =$ see MATLAB script

$V_{14} =$ see MATLAB script

Here τ_θ and τ_α are the torques in τ_x direction and, τ_ϕ and τ_β are torques in τ_y direction

CHAPTER 4
CONCLUSION

4.1 CONCLUSION

In this project, the modeling aspects of the BB8 spherical rolling robot have been developed. The proposed spherical mechanism consists of a 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. This counterweight acts like a pendulum with 2 DOFs which provides the 2D rolling motion around the transversal and longitudinal axes of the sphere. The Velocity Kinematics of the robot have been developed.

Highly nonlinear and coupled equations of motion along have been derived using the Euler-Lagrange method. Rolling motions around the transversal and longitudinal axes have then been decoupled in order to obtain a simpler state-space formulation for the equation of dynamic model.

We see a relation between the torque power and speed of the rolling. There is an increase in the power at the cost of reduction of speed; sometimes speed will increase with decrease in motive power depending on the type of surface it will have to traverse.

4.2 FUTURE SCOPE

Further scope of research may include the use of soft robotics to make the robot more mobile.

Having the base sphere split apart to deploy a dual leg mechanism on either side which can be actuated to make the robot jump and hence making it more mobile and allow it to reach previously unreachable areas.

One of the main drawbacks of spherical robots is the centre of mass shifting principle. By this principle virtually all spherical robot operations are severely limited by the maximum drive torque that can be generated. This torque limitation translates into a limit on the maximum inclination and highest obstacle that can be traversed by the spherical robot. A new mechanism using control moment gyroscopes for storing angular momentum which will effectively provide a spherical robot with a controllable torque boost can be modelled.

The spherical shell being sealed can also be used for either floating or submersion in liquid by changing pressures as and when required.