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Dynamic Simulation of a Reconfigurable Spherical Robot *

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***Abstract*—This paper describes the transformation process of a spherical robot into a configuration of two interconnected hemispheres with three omni-directional wheels. The spherical form of the robot facilitates ease of transport, storage and handling, whereas the wheeled configuration provides mobility and maneuverability. The transformation process is first analyzed in terms of an equation of motion, and its feasibility is validated using a dynamic simulation in MSC.ADAMS. The dynamic simulation results show that the robot can be reconfigured in any configuration. The largest torque required for the transformation occurs during the release of the robot legs while the flat sides of the two hemispheres facing the ground.**

***Index Terms*—Reconfigurable Robot, Spherical, Dynamic Simulation**

I. Introduction

With advancements in robotics technology, exploration of unsafe environments prohibitive to humans is now performed by robots. Because of the potentially hazardous conditions, the robot must be tele-operated to ensure the operator's safety.

For this type of missions, the robot can typically be shipped and deployed from an aircraft. Ease of storage, package, transport, and deployment constitute desirable properties of the robot design.

The conceptual design of the robot will be initially packed and deployed in a spherical configuration. The spherical construction offers ease in transportation and deployment; for example, a number of these robots can be packed and deployed together from an aircraft.

Additional cushioning materials for impact or landing can be conveniently installed on the spherical configuration as it has no sharp edges or corners. After landing, the robot may roll for extra distance. However, the maneuverability of spherical robot is limited to smooth surfaces due to its complex steering mechanisms.

This paper focuses on the transformation of the spherical robot into a configuration that allows for simple maneuverability. Actuators, sensors, and control systems must be designed so that they fit in a spherical shape. Though the spherical form may be potentially transformed into a variety of configurations, current attention is given to a simple configuration of two inter-connected hemispheres with three omni-directional wheels. We study the feasibility of the reconfigurable spherical robot by analytically deriving an equation of motion, and performing a dynamic simulation of the transformation process.

II. Background

The rolling sphere is considered to be nonholonomic. Recently, the study of nonholonomic systems has become increasingly attractive to researchers. Nonholonomic systems can be described as nonintegrable rate constraints resulting from rolling contact or conservation of momentum.

Many robotic locomotion systems designed based on this concept, e.g., wheeled robots, spacecrafts and underwater vehicles, have been shown using tools from differential geometry [1].

A number of robotic research studies have been done on constructing a spherical robot rolling on a plane. The locomotion of the spherical robot are mostly propelled by an internal mechanism with a single wheel resting on the bottom of the spherical shell [2], [3], [4].

A design proposed by Alves et al. [5] utilized the movement of the center of gravity of the spherical shell for steering. Koshiyama and Yamafuji [6] proposed a spherical robot design used two internal pendulums for moving its center of gravity.

Previous discussions on the steering mechanisms of the spherical robots illustrate the drawbacks of this design: the control algorithm is highly complex, and the maneuverability is limited by the steering procedure.

This paper proposes an alternative design for steering a spherical robot. Instead of controlling the rolling mechanism inside the sphere, the robot can transform into a mobile form with three omni-directional wheels. The wheeled configuration provides ease of control and movement in any directions.

III. Conceptual Design

This novel design of the spherical robot is based upon the concept of spherical shape to be used on a relatively flat surface. The original spherical shape provides mobility on the initial deployment and the compact shape of the robot.

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Fig. 1. A CAD rendering of Reconfigurable Spherical Robot

The current design requires a total of 6 motors: 3 for driving the omni-directional wheels, and the other 3 for releasing the leg-wheel mechanism. The two hemispheres will be locked and released by a solenoid mechanism. When the locking mechanism is released the two hemispheres will be will open up by torsional springs. The robot will be remotely control via radio frequency with a controller and power source on board, see Fig 1.

The robot design consists of two major mechanisms: (1) transformation of the spherical shape into two inter-connected hemispheres, and (2) deployment of the three omni-directional wheels.

After the initial rolling of the robot is terminated, the robot can be transformed into two inter-connected hemispheres with three omni-directional wheels for added mobility. Steering of the robot will be less complicated in the design with the use of three omni-directional wheels, see Fig 2.

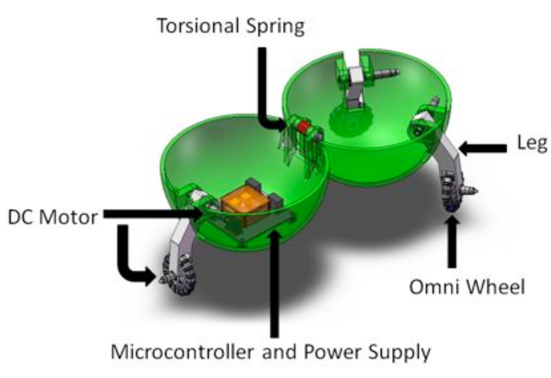

Fig. 2. During transformation

IV. Motion Model

This robot design consists of three possible motion models: (a) the rolling of the spherical robot upon deployment, (b) the transformation of the spherical form into a mobile configuration with two-interconnected hemispheres and three omni-direction wheels, and (c) the movement of the mobile configuration.

A. Spherical Rolling Model

A spherical robot is assumed to roll without slip after its deployment. The rolling motion can be illustrated in Fig 3.

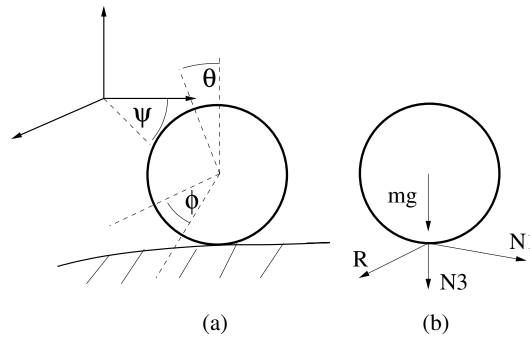

Fig. 3. (a) Spherical rolling (b) Free body diagram

Using Euler's equation for a rigid body, the equations of motion can be derived as:

$$\begin{aligned} \vec{M}_1 &= \bar{I}_1\dot{\omega}_1 + (\bar{I}_3 - \bar{I}_2)\omega_2\omega_3 \\ \vec{M}_2 &= \bar{I}_2\dot{\omega}_2 + (\bar{I}_1 - \bar{I}_3)\omega_1\omega_3 \\ \vec{M}_3 &= \bar{I}_3\dot{\omega}_3 + (\bar{I}_2 - \bar{I}_1)\omega_1\omega_2 \end{aligned}$$

where $\bar{I}_1 = \bar{I}_2 = \bar{I}_3 = \frac{2}{5}mr^2$ and R, N_2, N_3 are rolling force and reaction forces respectively, and the moments are:

$$\begin{aligned} \vec{M}_1 &= -rR \\ \vec{M}_2 &= r(N_! \cos\theta - N_3 \sin\theta)\cos\phi \\ \vec{M}_3 &= -r(N_1 \cos\theta - N_3 \sin\theta)\sin\phi \end{aligned}$$

B. Tranformation Model

After the initial rolling mechanism, the spherical robot may align in a random posture. In this work, two extreme postures are considered: (a) the hinge joint is in contact with the ground, and (b) the hinge joint is at the top of the sphere, see Fig 4.

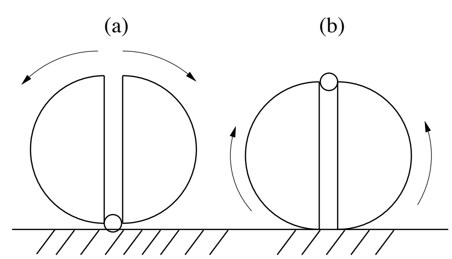

Fig. 4. Two possible posture during transformation (a) Hinge is on top (b) Hinge is at the bottom

Any other postures can be described as a variation of the two cases. Obviously, the transformation of the spherical robot in configuration (a) can be performed with ease because the opening of the shell has no external resistance.

On the other hand, the transformation of the robot in configuration (b) is non-trivial: (1) the opening mechanism must overcome friction at the robot-ground contact, and (2) the wheels must press against the ground to turn the hemispheres over. Hence, we consider case (b) as the limitation of the transformation process shown in Fig 5

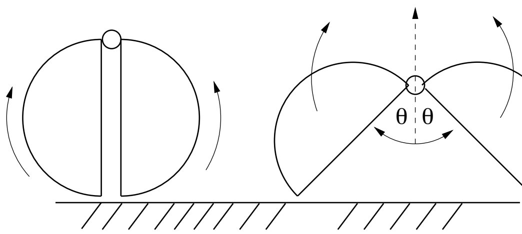

Fig. 5. During transformation

The free body diagram of one of the two hemispheres during the transformation can be shown in Fig 6.

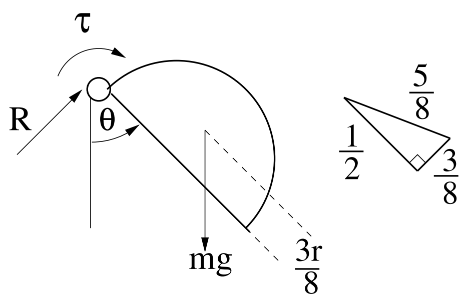

Fig. 6. Free body diagram of a hemisphere

Due to symmetry, the analysis was performed on one of the two hemispheres. There is torque τ due to torsional spring and damper, reaction force R and weight mg due to gravity acting on the hemisphere.

The equations of motion for this transformation can be determined using the work-energy approach. First, the kinetic energy of the hemisphere is given by:

$$T = \frac{1}{2}mv^2 + \frac{1}{2}\bar{I}\omega^2$$

where $v = \frac{5}{8}r\dot{\theta}$ and moment of inertia of the hemisphere $\bar{I} = \frac{83}{320}mr^2$

the total potential energy $V = V_e + V_g$ includes the contribution of a torsional spring ($V_e = \frac{1}{2}K_T\Delta\theta^2$) and the gravity ($V_g = -mg\bar{r}\sin\theta$)

Using Lagrange's equations of motion

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = \vec{\tau}$$

where $L = T - V$, we can derive the linearized equations of motion of the system as followed:

$$(\bar{I} + ml^2)\ddot{\theta} + k\theta - \bar{r}\theta = \vec{\tau} \qquad (1)$$

C. Three omni-directional wheels mobile robot model

The final stage of this robot is to transform into a three omni-directional wheels mobile robot similar to the configuration given in [7], [8]. To find the location of the robot, we used inverse kinematic model as shown in Fig 7.

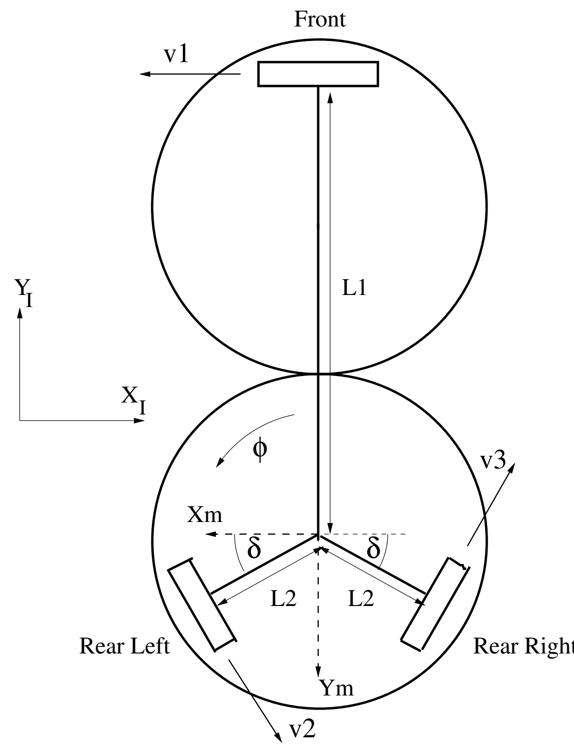

Fig. 7. Top view of kinematic diagram

The two rear wheels are offset by fixed angle δ and the velocity vector of each wheels is $v_i = R\dot{\theta}_i$ where $i = 1, 2, 3$ and R is the radius of the wheels. The initial frame is in the plane X_IY_I

The inverse kinematic equations are

$$\begin{aligned} v_1 &= \cos\phi\dot{x}_I + \sin\phi\dot{y}_I + L_1\dot{\phi} \\ v_2 &= -\sin(\delta+\phi)\dot{x}_I + \cos(\delta+\phi)\dot{y}_I + L_2\dot{\phi} \\ v_3 &= -\sin(\delta-\phi)\dot{x}_I - \cos(\delta-\phi)\dot{y}_I + L_2\dot{\phi} \end{aligned}$$

V. DYNAMIC SIMULATION RESULTS

This preliminary analysis assumes that in the undeployed configuration the robot is packed into a spherical aluminum shell with 200mm diameter and 5mm wall thickness.

The robot leg is 120mm long and the omni-directional wheel has a radius of 25mm. Battery, controller and other auxiliary equipments are simulated as a box size 80x80x40 mm^3 with a weight of 0.5kg. The total weight of the robot is approximately 2.5kg.

The feasibility of the transformation mechanism of the robot was verified by performing dynamic simulations using MSC.ADAMS [9].

The dynamic simulation was performed for the transformation process of configuration (a) (i.e, the hinge joint of the two inter-connected hemisphere is on the bottom or in contact with the ground).

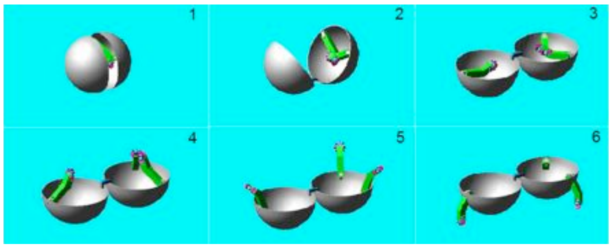

Fig. 8. Transformation process where hinged joint is on the ground

The opening mechanism shown in Fig 8 assumes that the contact between the spherical shell and the ground is frictionless. The transformation process of configuration (a) requires less amount of torque than configuration (b) because the three legs can be released without having to turn over the hemisphere.

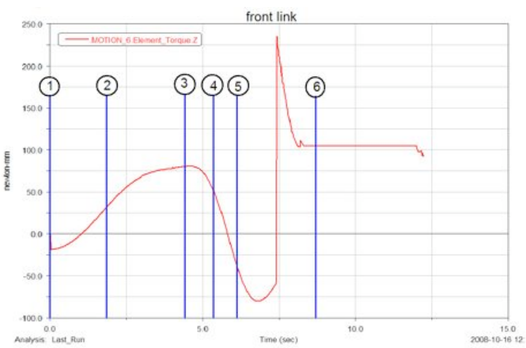

Fig. 9. Torque plot of Front Leg

Fig 9 shows the torque as a function of time for releasing the front leg in configuration (a). The maximum amount of torque of 225 N-mm is required in this process.

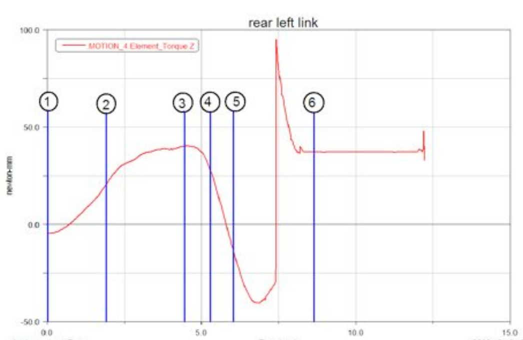

Fig. 10. Torque plot of Rear Left Leg

The maximum amount of torque required for the rear left leg shown in Fig 10 and for the rear right leg in Fig 11 are approximately 90 N-mm and 45 N-mm, respectively.

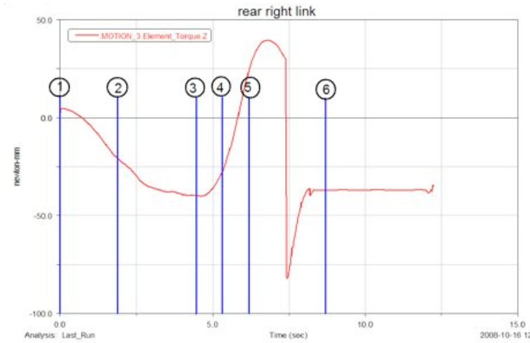

Fig. 11. Torque plot of Rear Right Leg

Another simulation was performed for the transformation process of the configuration (b) (i.e. the hinge joint of the two inter-connected hemisphere is on top) in Fig 12. It consists of the following steps:

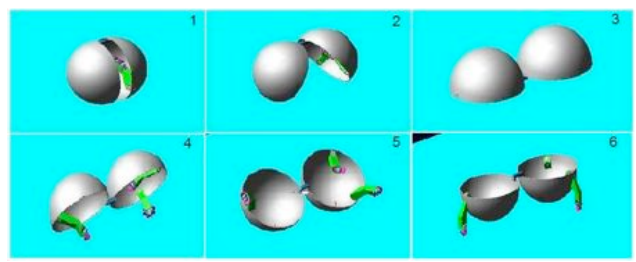

Fig. 12. Transformation process

1) the spherical shell opens up, and transforms into a configuration with two inter-connected hemispheres laying with the flat part on ground (Fig 12 step 1 to 2). The opening process is performed at the angular speed of 22.5 degree per second.
2) The robot wheels are released at the angular speed of 30 degree per second. The releasing wheels press against the ground, causing the hemispheres to turn over (Fig 12 step 3 to 4).
3) The hemispheres are lifted up off the ground. Analyses of the torque required during the transformation process are shown in Fig 12 step 5 to 6. In this process, the maximum amount of torque of 350N-mm is required at the rear legs.

Fig 13 shows the amount of torque required at the front leg during the transformation from stage 3 to 4. The maximum amount of torque of approximately 750N-mm is required to flip its body.

Fig 14 and Fig 15 shows the amount of torque required for motors for lifting the legs.

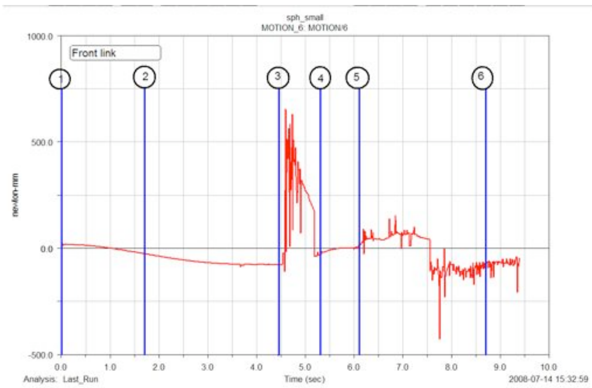

Fig. 13. Torque plot of Front Leg

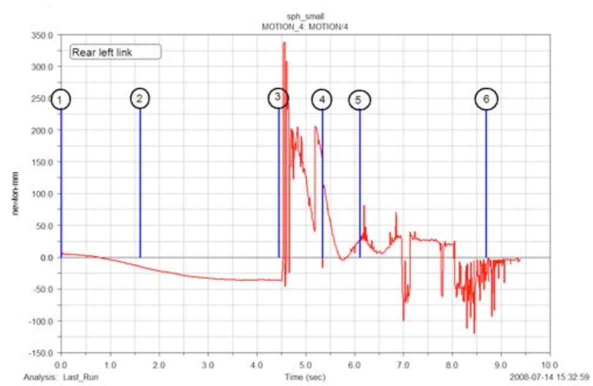

Fig. 14. Torque plot of Rear Left Leg

VI. Conclusion and Future Works

The reconfigurable spherical robot for exploration is being designed and developed at King Mongkut's University of Technology North Bangkok. The robot is initially packed into a spherical configuration. After deployment, the robot may transform into a mobile form with three legs equipped with omni-directional wheels. The dynamic simulation of the transformation process shows that the maximum torque is required during the turning over the hemispheres. The results confirm the feasibility of this robot design.

VII. ACKNOWLEDGMENTS

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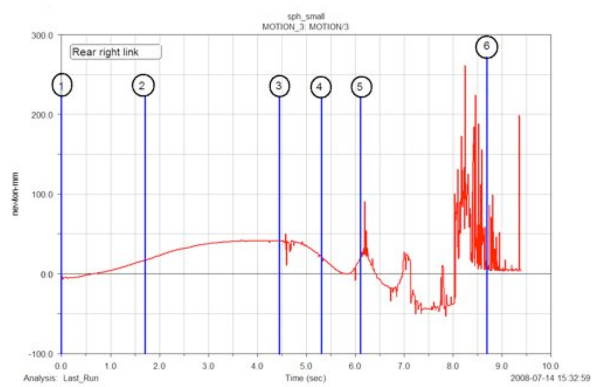

Fig. 15. Torque plot of Rear Right Leg

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