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Simulation of A Reconfigurable Spherical Robot IV for Confined Environment

Natthaphon Bun-Athuek
College of Industrial Technology
King Mongkut's University of Technology North Bangkok
Bangkok, Thailand
natthaphonb@kmutnb.ac.th

Pudit Laksanacharoen
Department of Mechanical and Aerospace Engineering
King Mongkut's University of Technology North Bangkok
Bangkok, Thailand
puditl@kmutnb.ac.th

***Abstract*—This work presents simulation of a Reconfigurable Spherical Robot IV for confined environment. The robot is a spherical shape with three legs kept inside spherical shell. Each leg has four degrees of freedom. All three legs can be extended for two types of locomotion such as legged locomotion and rolling sphere. A number of simulation has been done in steering in a wide and small radius of turning, rolling forward motion, and walking breaststroke concept. The simulation results show a promising concept of this new robot.**

***Index Terms*—spherical robot, reconfigurable spherical robot**

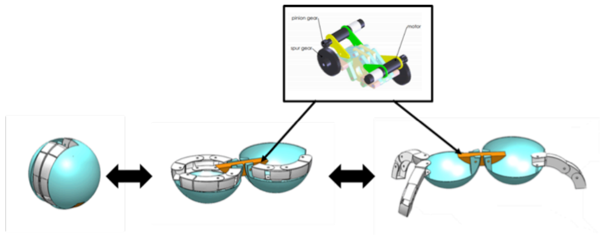

Fig. 1. Conceptual design of the new locomotion concept for Reconfigurable Spherical Robot IV

I. Introduction

Recently, robotic technology has become an integral parts of life such as manufacturing, medical technology, defense technology, and especially in search and rescue operation which is difficult to access. Therefore, many types of search and rescue robot are constructed to cope with high risk environment.

Spherical shape robot has become more interested among many robotic researchers because its spherical shape is versatile and protect all equipments kept inside the spherical shell. Another advantage of the spherical shape is that it can roll down on the slope which will save energy for locomotion.

The early development of spherical mobile robot was developed by Halme et al. [5]. The robot is driven by inside drive unit (IDU) which is a motor driven wheel inside the shell. Joochim et al. [4] proposed a spherical rolling robot with internal driving mechanisms. Bicchi et al. [6] introduces the SPHERICLE with a small car balancing the rolling movement of the robot. Asama et al. [7] invented Moball which is an internal triaxial set of linear electromagnetic generator kept inside a spherical frame. The movement of Moball is created by changing the magnetic flux inside the spherical frame. Morinaga et al. [9] studies a spherical rolling robot driven by two internal rotors. Most of the spherical robot is driven by internal mechanism to create movement.

In recent studies, H. Xing et al. [8] proposed an innovative small turtle-like Amphibious Spherical Robot (ASRobot) which has four legs and is able to move underwater. This paper studies the spherical robot with three legs. Our previous work have developed three generations of spherical robot which each generation has different types of locomotion: leg expansion with omnidirectional wheels, legged locomotion, rolling with spherical shape [10]- [13]. Nevertheless, the previous reconfigurable spherical robots required spacious environment due to transformation process and they can not move in confined environment. We then design and develop reconfigurable spherical robot IV to enhance its locomotion in a confined space. In addition, the robot should be able to change its direction while in spherical shape. The robot still preserves its transformation from spherical shape into legged locomotion.

II. Design Concept

Fig. 1 shows the reconfigurable spherical robot IV. The robot is consisted of two inter connected hemispheres with four bar mechanism driven by a DC motor [15]. One side of hemispheres has one leg installed and the other side of hemisphere has two legs installed. Each leg is designed to be able to perform multifunctions. For three legs to be able to move like butterfly swimming concepts [14] .

The robot is designed to weigh about 5 kg and its center of mass is located on left leg and back leg touch the ground while in spherical shape. The robot has 350 mm in diameter. After its transformation into two connected hemispheres, the robot has 850 mm in length and 500 in width. The height measured from the lowest point of curve is about 50 mm above ground. Each leg inspired by human arm has four degrees of freedom as shown in Fig. 2. Leg components are consisted of a total of four degrees of freedom; two degrees of freedom shoulder joint (joint 1 and joint 2), one degree of freedom at elbow joint (joint 3), and wrist joint (joint 4).

The design of reconfigurable spherical robot IV is able to move by rolling using three legs pushing its body forward. In a narrow path where wheel movement is not possible the robot uses its leg to propel its movement and control its direction as shown in Fig. 4.

III. Leg Kinematic Model

Each leg has four degrees of freedom. The D-H parameters of each leg is shown in table I and Fig. 3.

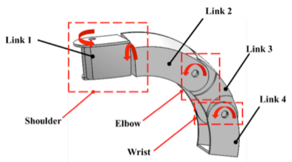

Fig. 2. Leg Design

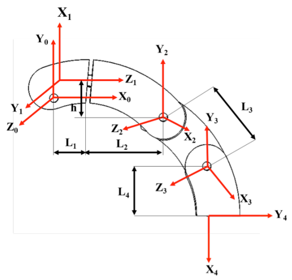

Fig. 3. Leg kinematics

No	α_i	a_i	d_i	θ_i
1	$\frac{\pi}{2}$	0	0	θ_1
2	-$\frac{\pi}{2}$	a	$L_1 + L_2$	θ_2
3	0	L_3	0	θ_3
4	0	L_4	0	θ_4

TABLE I
DH PARAMETER OF ROBOT'S LEG

$$T_{01} = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ -\sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{12} = \begin{bmatrix} \cos\theta_2 & 0 & -\sin\theta_2 & a\cos\theta_2 \\ \sin\theta_2 & 0 & \cos\theta_2 & a\sin\theta_2 \\ 0 & -1 & 0 & L_1 + L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{23} = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & L_3\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & \cos\theta_2 & L_3\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

IV. Robot Simulation

The robot simulation has been performed in MATLAB Simulink in conjunction with SolidWorks. The robot model is designed to touch the ground. The ground contact is modeled as PD control.

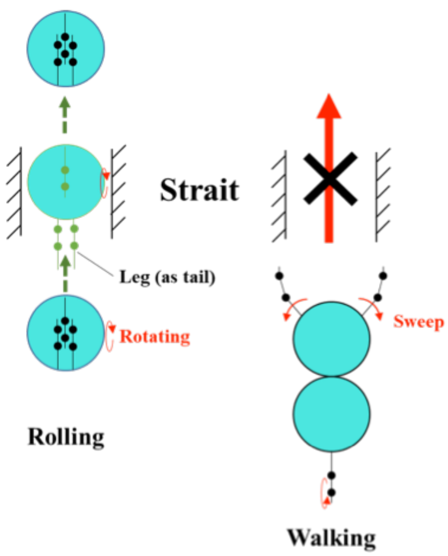

Fig. 4. Conceptual design for narrow path locomotion

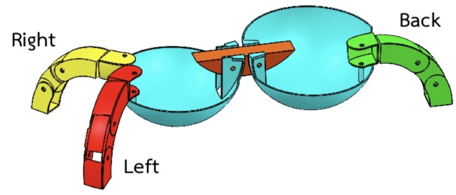

Fig. 5. Reconfigurable Spherical Robot IV in expansion mode

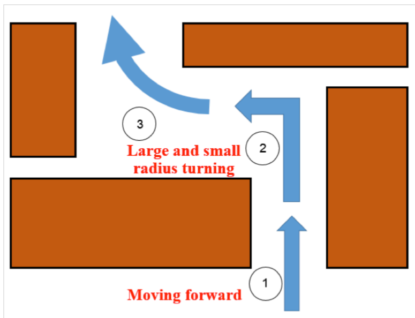

Fig. 6. Rolling simulation

A. Rolling motion

The rolling simulation shows step by step of robot 's leg to propel its movement for rolling. We simulated the robot to rolling into a labyrinth with a narrow path. The simulation experiments of the robot is classified into three types as shown in Fig. 6.

1) Forward motion: While in spherical mode, the center of mass of the robot causes the robot's left leg and back leg to touch the floor. When the robot starts to move, it starts using the shoulder joint (joint 1). The robot's left and back legs are pushed down to the ground by using the speed and angle of each part of both legs equally, so that the reaction forces in the act of ejecting to exert the force pushing the robot to move forward by rolling motion. The initial condition of the left leg is given as angular velocity ω = 12.12 rad/s and angular displacement θ_{1L} = 90 degrees. The initial condition of the back leg is given as angular velocity ω = 12.12 rad/s and angular displacement θ_{1R} = 93 degrees. The other joint parameters initial conditions are zero. Once the robot has ro lled one cycle, it will be in the condition that the left and back leg touch the ground to prepare for the next movement as shown in Fig. 7. Fig. 8 shows the robot's forward movement by using its legs to flip it Fig. 9 shows the part of the robot's forward movement by using its legs to flip itself forward.

2) Steering motion: Streering motion of the robot can be done by using the net effect of force from left leg and back leg to the ground. Two forces can cause reaction forces to push the robot into the desired direction as shown in Fig. 10.

It shows that when the forces on both legs are not the same amount acting to the ground causes the robot to turn. The radius of turning of the robot can be determined by the difference in magnitude of the robot's legs on ground. Therefore, the steering motion can be divided into two cases as the following

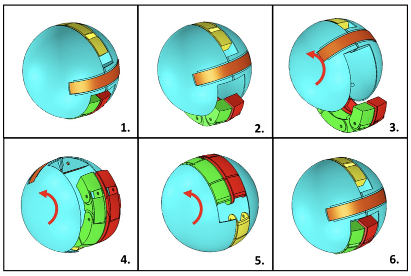

Fig. 7. Forward rolling concept where left and back leg push simultaneourly

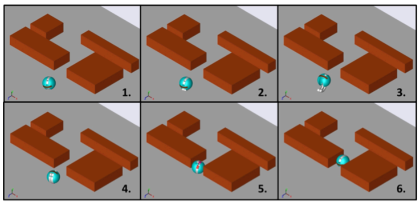

Fig. 8. Forward rolling concept of the robot

a) Steering in small radius of turning : It is a movement of the robot in a spherical shape, in which the robot's center of gravity causes the robot's left leg and back leg on the floor. When the robot starts to move, it starts using the shoulder joint 1 of the robot's left leg and back leg to push down to the ground using the speed of movement of each part of both legs, which is slightly different in order to create the reaction force of pushing or ejecting both legs slightly unbalanced. The initial condition of the left leg

This causes the robot to roll while simultaneously turning as well as using the legs that flip on both sides of the different sides back to its starting position. Once the robot has successfully rolled one cycle, the condition will then be repeated. Fig. 11 shows the robot's small turning radius by flipping its leg. Fig. 12 shows the small radius of turning of the robot.

b) Steering in wide radius of turning: It is a movement of the robot in a spherical shape in which the joint 1 of the robot is pressed down to the ground with differentiate speed of movement of the two legs. This will create unbalanced force to exert or propelled its body. It will cause the robot to roll with a sudden turning. For the next rolling cycling, the condition will begin by left leg and back leg touch the ground and then repeat all over again.

B. Walking Motion

The concept of three-legged walking for this robot use the idea of butterfly swimming or breaststroke concept where

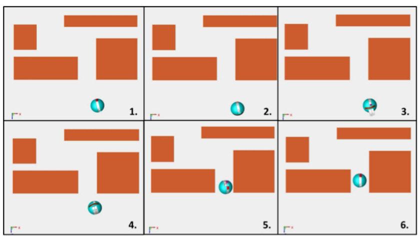

Fig. 9. Forward movement using its own legs to flip forward

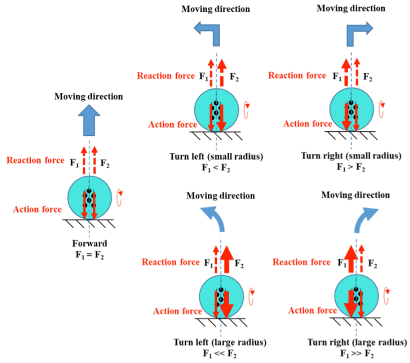

Fig. 10. Steering motion of the robot

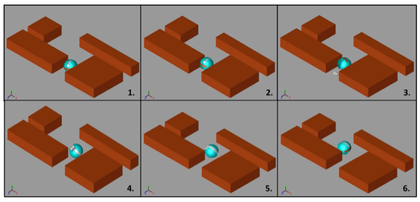

Fig. 11. Small turning radius by flipping its leg

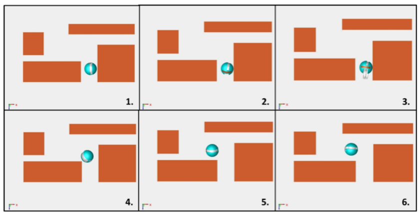

Fig. 12. Small radius of turning of the robot

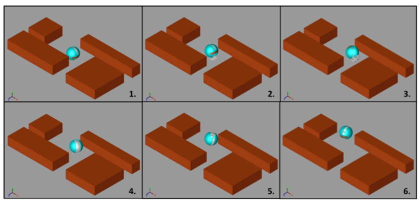

Fig. 13. Wide turning radius using its own legs

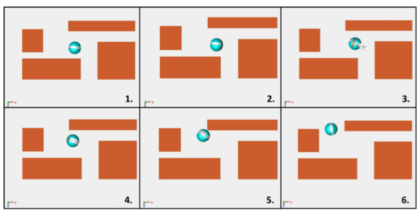

Fig. 14. Wide radius of turning

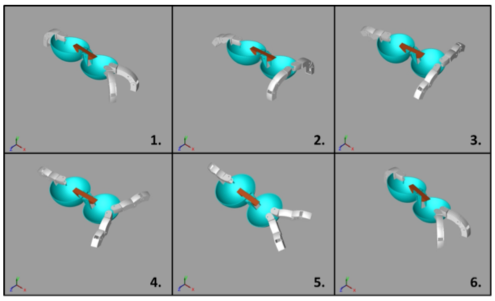

Fig. 15. Breaststroke walking concept of reconfigurable spherical robot IV

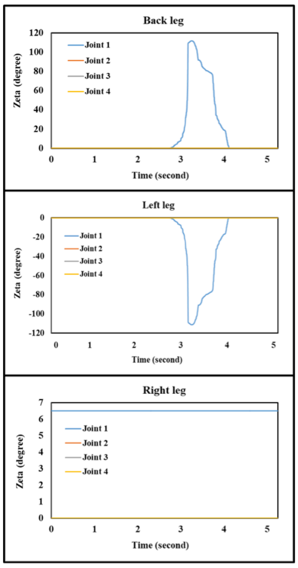

Fig. 16. Angular position of each joint

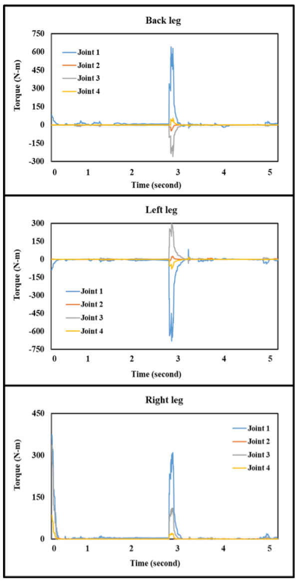

Fig. 17. The amount of torque used in each leg of the robot to pull itself to move forward

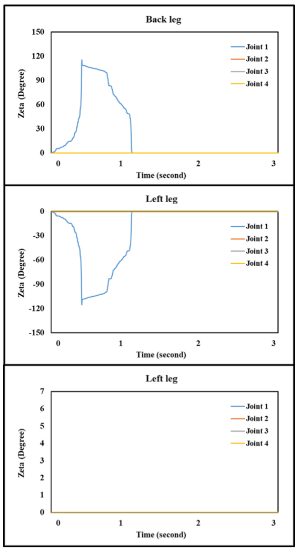

Fig. 18. Position of the links in each robot's legs

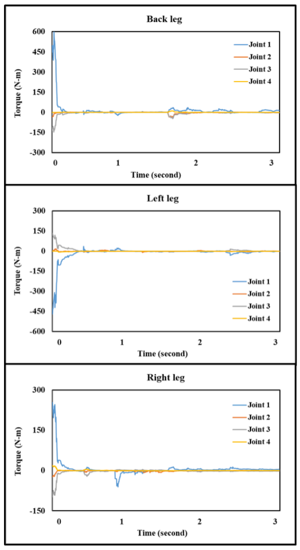

Fig. 19. The amount of torque used in each leg of the robot to pull itself to move forward

two front legs crawling symmeterically in circle accompanied by the rear leg kick. The simulation of breaststroke walking is shown in Fig. 15

V. Simulation Results

A. Rolling motion

1) Forward movement: Fig. 16 shows the angular position of each joint in robot's legs. In order to allow the robot to flip itself forward by changing the degree of joint 1 from 0 degrees to 110 degrees while the other parts maintain the same position. Fig. 17 shows the amount of torque used in each leg of the robot to pull itself to move forward. It is found that the amount of torque used in the joint 1 which has the amount of 600 Nm while joint 3 is the second largest load about 300 Nm. Note that the robot's rear legs and left legs use the same amount of torque to walk on the ground. The robot can move successfully in the desired direction without right leg movement.

2) Turning with small radius of curvature: Fig. 18 shows the position of the links in each robot's legs. In order to allow the robot to eject itself to change its direction in a small radius of curvature by changing the angular displacement of link 1 from 0 degrees to 110 degrees while the other parts are still in the same position. Fig. 19 shows the amount of torque used in each leg of the robot to move forward. The maximum amount of torque at joint 1 is about 600 Nm. Joint 3 is the second highest amount of torque about 150 Nm. Noticed that the back leg and left leg use the different amount of torque at the position of joint 1 about 150 Nm.

3) Wide turning radius of curvature: Fig. 20 shows the position of the links in each robot's legs. In order to allow the robot to eject itself to change its direction in a wide turning radius by changing the degree of link 1 from 0 degrees to 110 degrees while the other parts maintain the same position. Fig. 21 shows forward movement torque. The amount of joint torque of approximately 600 Nm is the maximum torque that occurs in the operation of the robot while joint 3 has the second highest torque. burden It is necessary to use approximately 150 Nm of torque. By observing that the back and left legs of the robot will use the torque at the joint 1 position down to the ground in approximately 375 Nm, so it can enable the robot to move. In the desired direction with a wide radius successfully the angular position of the right leg is approximately 8 degrees of movement to to maintain the balance of the robot's rolling in this process.

4) Walking movement: Fig. 22 shows the torque of the robot legs, transforming each sphere while moving by breaststroke walking concept. In the period of 0 to 10 seconds, a period in which the robot's right leg and left leg are sweeping back and forth with the pushed rear leg to move the robot forward. In the 10-20 seconds, the three legs are raised to prepare to sweep back to the starting position. In the second part of the 20-30 seconds, the rhythm of the left and right legs sweeps back to the starting position. The rear legs are in the same fixed position. After 30-40 seconds, all three legs of the robot will be pushed down to the floor to lift the robot up from the floor and prepare to work at the next walking cycle.

VI. Conclusion

The simulation of reconfigurable spherical robot IV has completed with the ability to walk with breaststroke walking concept and roaming in the confined environment. The robot

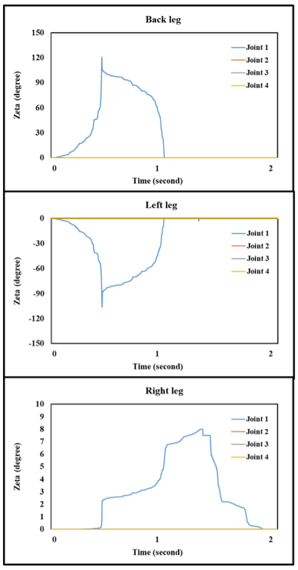

Fig. 20. Position of the links in each robot's legs

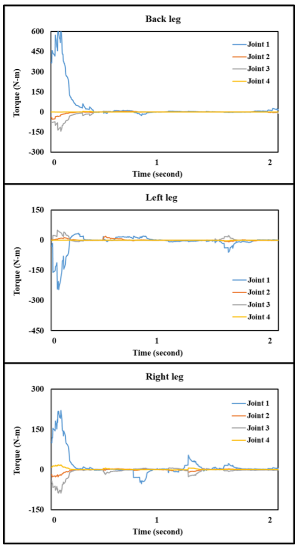

Fig. 21. Forward movement torque

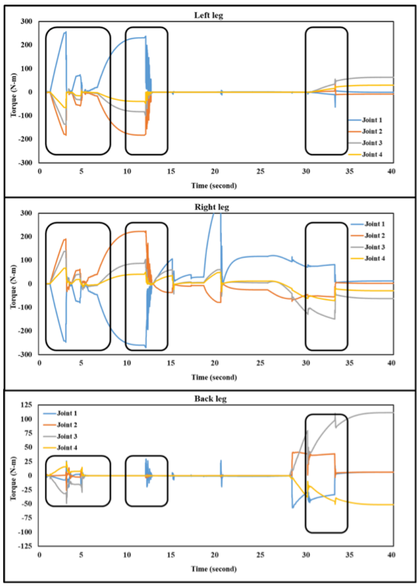

Fig. 22. Torque of the robot legs, transforming each sphere while moving by breaststroke walking concept

is able to roll as its transform into spherical shape. The direction of movement can be controlled by using its leg for steering. In future work, we plan to construct the robot for testing the simulation concept.

ACKNOWLEDGMENT

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