A new locomotion concept using shell transformation for a Reconfigurable Spherical Robot
แนวคิดการเคลื่อนที่แบบใหม่โดยใช้การแปลงร่างสำหรับหุ่นยนต์ทรงกลม

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Abstract

This paper presents a new locomotion concept for a reconfigurable Spherical Robot. The robot is a spherical shape that can be transformed into two hemispherical shapes with three omnidirectional wheels. Each side of hemispherical shapes can split into three shell segments where each segment is connected to a leg with three degrees of freedom. At the tip of each leg kept inside this shell is equipped with an omnidirectional wheel. The robot can perform two locomotions: (1) rolling using shell transformation and (2) moving with three omnidirectional wheels. The test results show that this robot can go forward with rolling using shell transformation and moving with three omnidirectional wheels successfully.

Keywords: Shell transformation, Reconfigurable Spherical Robot

1. Introduction

In recent years, robotic technology has become prevalent in many types of industry such as food industry, military operation, hotel services, rescue operation especially in dangerous environments (Nozaki, H., et al., 2018). The design of each robot task has become the primary concern to fulfill each mission. The reconfigurable spherical robot is designed to keep all parts such as surveillance camera, communication equipment, and robot legs inside the spherical shell to protect them from damage during transportation of hazardous environments (Nakashima, A., et al., 2018).

In recent works of our research (Jearanaisilawong, P., et al., 2009), (Manoonpong, P. and Laksanacharoen, P., 2014), (Bunathuek, N. and Laksanacharoen, P., 2017), (Bunathuek, N., et al., 2014) we have demonstrated concept and design of reconfigurable spherical robot that can move using omnidirectional wheels equipped at the end of each leg or legged movement. However, our previous robots show that rolling of spherical shape requires external forces or force of gravity which causes the uncontrollability. This work proposed a new type of locomotion called shell transformation. This locomotion use the outer shell of the hemisphere to push against the floor for movement. The outer shell of the spherical shape can split into three shell segments to hit the floor alternately for movement. The shell transformation can be controlled by flexion and extension from each shell segment. It can also help the robot to navigate while in spherical shape. It is also safe for internal parts while rolling. This type of locomotion will enable the movement of the robot to move across rough surface and can possibly move across narrow path. With the additional mobility of the robot, this will make the robot be able to do much more maneuvering in different types of environment.

2. Research purpose

2.1 The purpose of this research is to design and construct the reconfigurable spherical robot with two types of locomotion: (1) rolling using shell transformation and (2) moving with omnidirectional wheels.

2.2 The study includes the robot control for the two types of locomotion.

3. Method

3.1 Conceptual Design

Our previous spherical robot has two inter-connected hemispherical shapes which require more space during its transformation. In addition, the direction of movement cannot be controlled by any internal equipment. Our previous robots have inspired us to design a new version of a reconfigurable spherical robot which can be controllable while in spherical shape. Locomotion design of the robot was inspired from Whegs (Tantichattanont, P., et al., 2007), (Quinn, R.D., et al., 2001) which are a type of robot that has the combination of wheels and legs. Figure 1 shows the shell transformation movements as spoke wheel mechanism with three appendages. The tip of the appendages create discontinuous contact point. This work utilize the spherical shell as the surface contact to create more stability. These appendages are shell segments arranged evenly with an angle of 120 degrees apart.

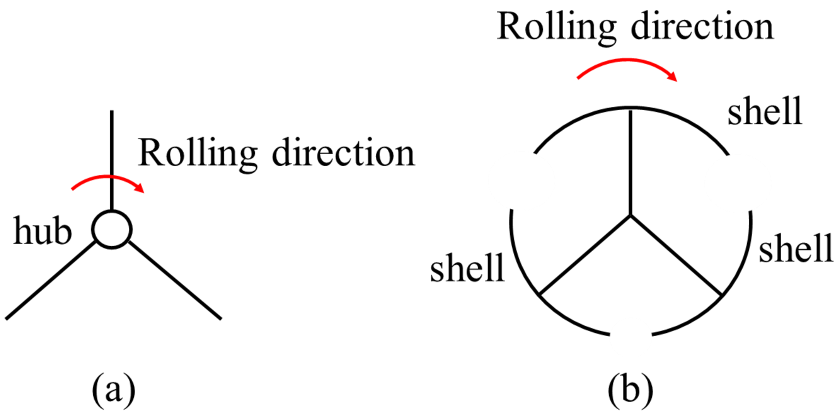

Figure 1 Schematic diagram for (a) whegs™ with three appendages (b) the reconfigurable spherical robot with three flexion outer shells.

We use the concept of shell transformation by splitting each side of hemispherical shape into three shell segments. Each shell segment can be flexed and extended independently. There are a total of six shell segments. There is an omnidirectional wheel installed on the inside structure of the shell segment to create wheel movement. The robot can perform two types of locomotion: rolling by shell transformation and wheel movement by the omnidirectional wheels. Those two types of locomotion require changing the center of gravity of the robot to create the internal forces so that the robot can move in the desired direction. While the outer shell of spherical shape can still protect internal parts of the robot. This work is focused on the robot's locomotion on flat ground and will extend to grass and rough terrain. The flexion and extension of the leg creates shell movement in rolling robot as shown in Figure 2. The spherical shape of the robot has a diameter of 365 mm (the spherical shape is formed by fiberglass).

The spherical shape can be transformed into two inter- connected hemispherical shapes; white and red. Each side of the hemisphere consists of three legs attached with outer shell segments (the omnidirectional wheels with a diameter of 50 mm are installed at the end of spherical structure for wheel movement) and the other end of each leg is connected to a microcontroller as shown in Figure 3. The microcontroller board is installed in the center of the robot so that it can be kept inside the spherical shell. The robot weighs about 5 kg.

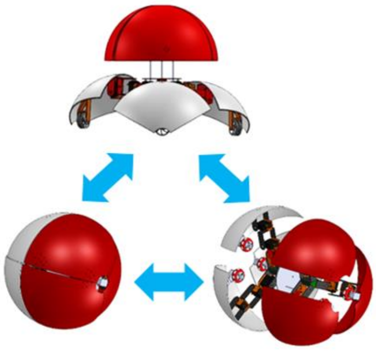

Figure 2 Conceptual design of the new locomotion concept.

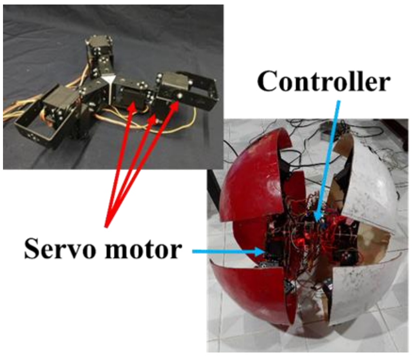

Figure 3 Three legs segment on each hemispherical shell.

3.2 Actuator selection

In order for the robot to change its center of gravity as planned, we need to select the proper types of actuator in which it can be defined as the following

1) Magnitude of forces on each leg

When the robot is in spherical shape and ready for rolling. There are four contact points which can calculate the amount of force for each leg as

$$4R = mg \tag{1}$$

Where: R is reaction force in N, m is mass in kg, g = gravity in m/s^2Therefore, 4R = 5x9.81, The forces on each leg R = 12.2625 N

2) Size of servomotors

To select the size of servomotors we have to calculate the amount of torque on each joint and distance from the exerted force to servomotor. With the assumption of the exerted force to the distance has the length of 70 mm. The amount of torque can be calculated as

$$T = Fxr \quad (2)$$

Where: T is Torque in N-m, F is Normal exerted Force on distance of servomotor in N, r is distance of servomotors to the force

Therefore, T = 12.2625x0.070
The forces on each leg T = 0.8583 N-m

With a safety factor of 1.5, we will use the servo motor with the minimum torque as 1.5x0.85 = 1.275 Nm. We then choose the servomotor off the shelf with the torque of 1.4715 N-m (15 kg-cm).

3.3 Robot Controller Design

To achieve high productivity, the robot has been equipped with multiple actuators and controllers as shown in Figure 4. The controller receives a start command from human to computer via USB cable to controller signal generator. Then, the Arduino Uno generates control signal with motor driver L298N dual motor Controller Module and 16 channel PWM servo drive module (12-bit PWM with I2C interface) PCA9685 sends control signal to DC gear motor (2.4-3.0 V), hyper-dash 3 motors to drive the omnidirectional wheels. The 18 servo motors MG996r 7.2 V with maximum torque of 11 kgf-cm speed 0.13 s/60 degrees drive the robot leg. There are two sensors to sense its location and orientation installed on this robot: GPS module GY-NEO6MV2 and gyroscope module GY 521 MPU6050.

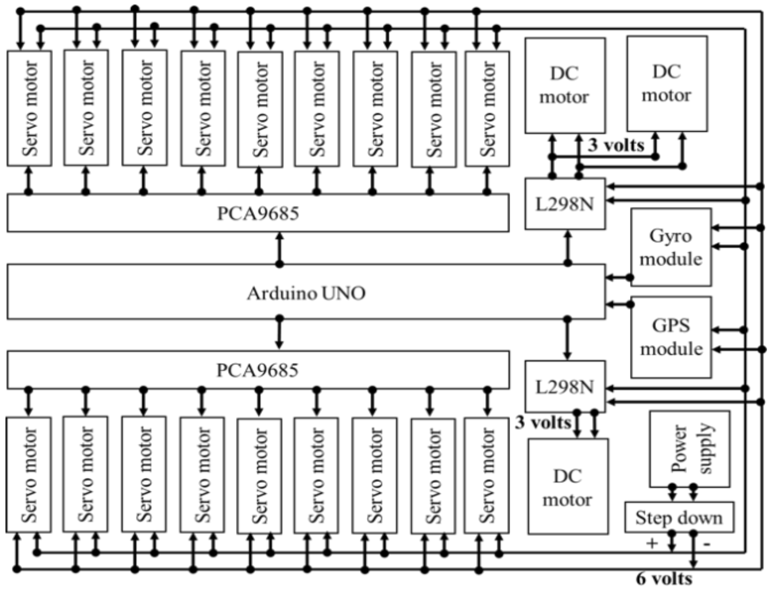

Figure 4 Schematic Diagram of the reconfigurable spherical robot.

3.4 Locomotion concept

1) Rolling using shell transformation

(1.1) Rolling forward

The shell transformation of the robot is to change its center of gravity. The weight of the robot will drive its body into defined direction as shown in Figure 5. The shell transformation can be described when forward direction moving as the following; 1) the robot legs are expand fully into spherical shape, 2) one shell No. 2 is tugged in so that the CG has changed and the weight of the robot drive the spherical in clockwise direction in step 3 and 4, once the shell No. 2 has moved into the rear the leg are expanded again to bring back the spherical shape and then start over again. Figure 6 shows kinematics analysis of the shell transformation movement of the robot.

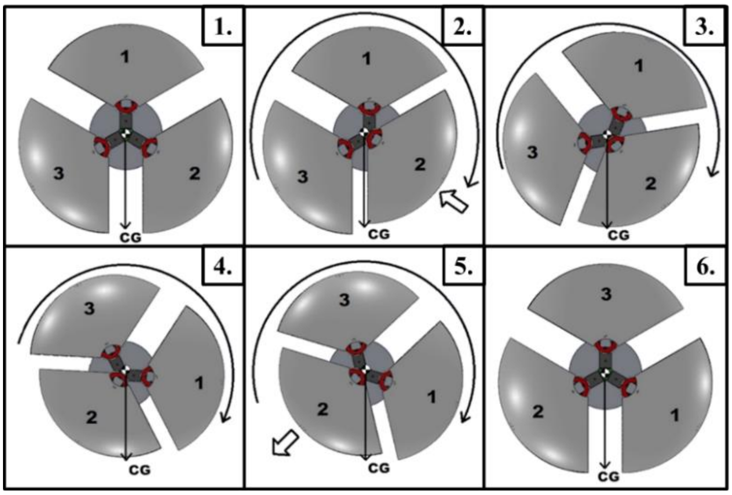

Figure 5. Shell transformation of the robot.

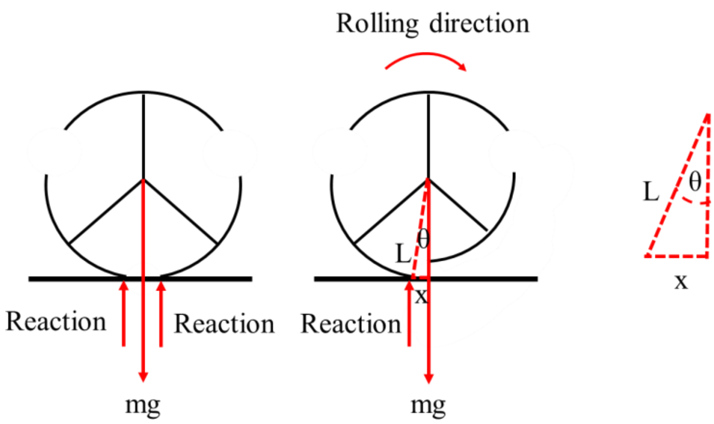

Figure 6. Robot's rolling motion illustrated.

$$\sum \tau = I\alpha \tag{3}$$

$$mg\left(L\sin\theta\right) = I\ddot{\theta} \tag{4}$$

When $\theta \approx 0$, $\sin\theta \approx \theta$

$$I\ddot{\theta} - mgL\theta = 0 \tag{5}$$

$$\ddot{\theta} + K\theta = 0,\ K = -\frac{mgL}{I} \tag{6}$$

Where; m is mass of the robot, g is gravity, L is radius of the robot while extending, I is mass moment of inertia, θ is angle between support and center of gravity.

(1.2) Steering Motion

Steering motion uses the same concept as the rolling forward but adjusting its shell extension segment to support its weight to control its center of mass to move to a desired direction.

2) Moving with three Omnidirectional Wheels

One side of the hemisphere kept its shape and the other side expanded three shell segments to allow the three omnidirectional wheels to touch the ground. The configuration and vector analysis are shown in Figure 7.

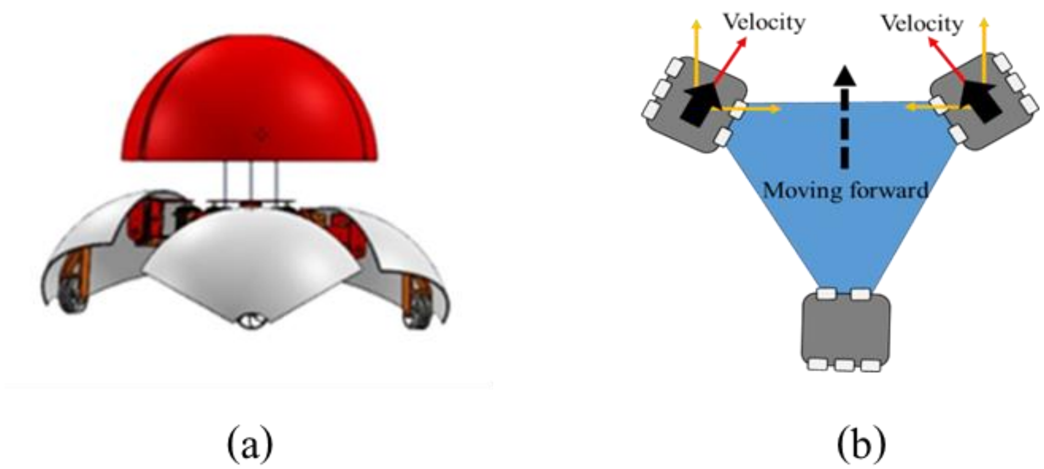

Figure 7 (a) Robot transformation into three omni directional wheels (b) vector algebra to drive the robot in the defined direction.

3.5 Performance Analysis

1) Rolling using shell transformation

(1.1) Rolling forward

A number of experiments have been analyzed in different types of surface such as flat ground, grass, rough terrain. We estimated the velocity for the rolling forward by measuring distance travel within a timeframe. We can then use the velocity equation to calculate the velocity as shown here.

$$v = \frac{\Delta s}{\Delta t} \tag{7}$$

where; v is the average velocity of the robot in m/s, Δs is the travel distance in meter, Δt is time in sec

(1.2) Steering motion

This test was done on flat ground only. We time when the robot starts to transform until it finishes its steering to sharp left or right. The velocity of the robot can be calculated as the angular velocity.

$$\omega = \frac{\Delta \theta}{\Delta t} \tag{8}$$

Where; ω is average angular velocity of the robot in rad/s, $\Delta \theta$ is angular displacement in rad, Δt is time in sec

2) Moving with three Omnidirectional Wheels

Similarly, we estimated the velocity for the Moving forward with three Omnidirectional Wheels by measuring distance travel within a timeframe. We used the same velocity equation to calculate the velocity as shown in section 3.5.1.

4. Results

For all experiments of rolling forward and steering motion, we have tested approximately 5 times respectively as shown in Table 1. The average velocity can be calculated. We then could separate the experiments result into 2 parts as following

Table 1 Speed of reconfigurable spherical robot

No.	Moving Forward (m/s)				Steering motion (rad/s)
	Rolling			Wheel	Turn left and right
	Flat ground	Glass	rough terrain	Flat ground	Flat ground
1	0.334	0.213	0.293	0.363	0.610
2	0.337	0.276	0.287	0.389	0.675
3	0.356	0.237	0.278	0.397	0.623
4	0.342	0.256	0.276	0.387	0.610
5	0.325	0.257	0.291	0.389	0.631

4.1 Shell transformation results

Figures 8-10 exhibited that the robot is capable of moving with the speed of 0.339, 0.247 and 0.285 m/s on flat ground, grass, rough terrain respectively. Figure 11 shows that the robot is capable to transform until it finished its steering to sharp left or right with the speed of 0.629 rad/s on flat ground.

4.2 Omni directional wheels transformation

Figure 12 shows the robot transformation from spherical shape into omni-wheels configuration. The omni-wheels are attached to the end of each robot leg. The robot can move with the speed of 0.385 m/s. Nevertheless, the robot must be hanged from the pole since its omni-wheels can not fully support its body weight.

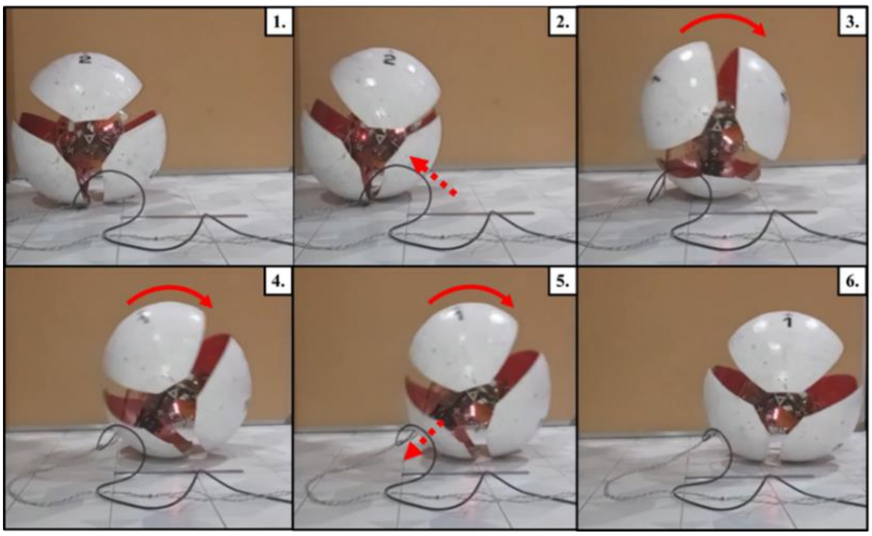

Figure 8 Robot shell transformation on flat ground.

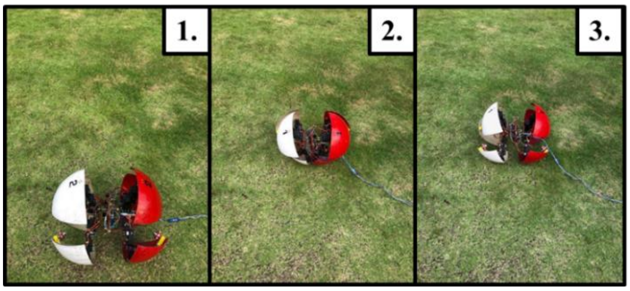

Figure 9 Robot shell transformation on grass.

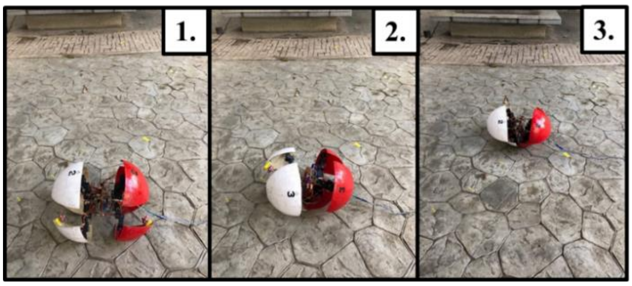

Figure 10 Robot shell transformation on rough terrain.

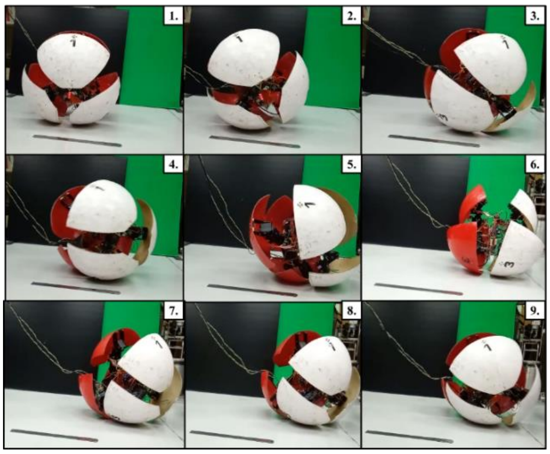

Figure 11 Robot shell transformation to sharp left or right on flat ground.

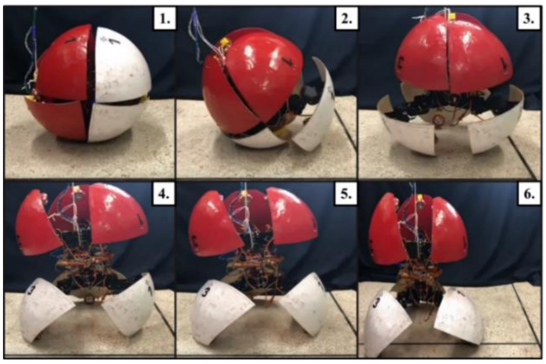

Figure 12 Robot omnidirectional wheels transformation.

5. Discussion and conclusion

We have successfully constructed a new type of spherical robot which can be transformed into two types of motion: rolling and wheel movement. The rolling locomotion used its shell transformation driven by 18 internal servomotors. The robot is capable of rolling forward on different types of surface such as flat ground, grass and rough terrain. For steering motion, the robot also used shell transformation as moving forward but it requires several steps more than forward movement to keep its balance so that the robot will not tip over. This work presents steering motion on flat ground only. We can foresee that the robot can possibly move in a narrow path but not able to move up to slope or staircase. For wheel movement using three omnidirectional wheels can move with the velocity of 0.385 m/s. However, the robot is tethered with cable to help support its body while moving on wheels. However, the new type of spherical robot is able to move forward faster than our previous work with the velocity of 0.068 m/s and 0.05 m/s respectively. The new robot is still tethered with external power sources so the robot is not able to travel independently. For future work, we plan to implement internal power sources and add additional rolling concepts for the robot.

6. Acknowledgements

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