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Design of Quadruped Walking Robot with Spherical Shell

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ABSTRACT

We propose a new quadruped walking robot with a spherical shell, called "QRoSS." QRoSS is a transformable robot that can store its legs in the spherical shell. The shell not only absorbs external forces from all directions, but also improves mobile performance because of its round shape. In rescue operations at a disaster site, carrying robots into a site is dangerous for operators because doing so may result in a second accident. If QRoSS is used, instead of carrying robots in, they are thrown in, making the operation safe and easy. This paper reports details of the design concept and development of the prototype model. Basic experiments were conducted to verify performance, which includes landing, rising and walking through a series of movements.

1. Introduction

Recently, many mobile robots have been developed to investigate and perform rescue operations at disaster sites where it is difficult for operators to enter. Two examples are the 510 Packbot (iRobot 510 PackBot, 2013), a commercial product, and Quince (Rohmer et al., 2013), both of which are in practical use. We believe that wide range searches using many small, inexpensive robots dedicated to search operations are effective in finding victims quickly.

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However, carrying robots into a disaster site is dangerous; operators may be injured carrying them in, resulting in a second accident. Throwing the robots in over uneven terrain results in a safer, easier way of getting the robot into the site. Various search robots that can be thrown have been developed for military or security use. The packbot 110 FirstLook, made by iRobot, is a small type crawler vehicle with two flipper arms; it can climb over obstacles using its arms (iRobot 110 FirstLook, 2013). The SandFlea, made by Boston Dynamics, is a small wheel type vehicle comprising four wheels and a jump mechanism. It can move and jump over high steps using gas power (Boston Dynamics SandFlea, 2013). The Throwbot, made by Recon Robotics, comprises a column body and two wheels. It can be operated by wireless controller (Recon Robotics Throwbot, 2013). Each of these robots is small, very lightweight and resistant to shock. Their wheels or crawler belt on the ends of their body and absorbs shock, so landing on a flat surface is fine. However, landing on uneven surfaces such as rubble in a disaster site causes shock to the robot body. We believe this robot needs shock absorbent materials that can withstand external force from all directions.

Walking robots can contact the ground over discrete points and the contact points can be arbitrarily selected according to terrain features. Recently, some robots have been field tested on uneven terrains with good results. The LittleDog (Buchli et al., 2009) and The BigDog (Boston Dynamics BigDog, 2013) are well-known quadruped walking robots made by Boston Dynamics; performance was tested by having them walk on easily collapsed rubble and on a mountain surface. The Titan X (Hodoshima *et al*, 2010) is a hybrid quadruped Walking Robot with the mobility of a crawler vehicle. Each leg mechanism has a crawler belt that can also be used as a drive train. The Titan X demonstrates proper performance over irregular ground using crawler mode and walking mode. Previous robots did not have a shock-proof function to protect the robot when it falls. Consequently, it was difficult for them to walk over irregular ground. Neither did they have the kinematic performance needed to recover from a fall.

We propose and aim to develop a new quadrupedal walking robot called "QroSS," which has a spherical outer shell and features walking mode and shock-proof mode. The mechanical design is reported here. The remainder of this paper is organized as follows: Section II overviews and discusses the design concept; Section III gives details of mechanical design; Section IV presents considerations on rising motions; and Section V presents and discusses basic experiments.

2. Design Concept

We assume the following rescue scenario for our robot, shown in Figure 1: a) getting investigation robot into disaster site from safe area by throwing, b) landing on rubble while absorbing shock, c) rising by extending its legs, and d) investigation by walking mode. QRoSS design requirements are that it must be shock absorbent, mobile and recoverable.

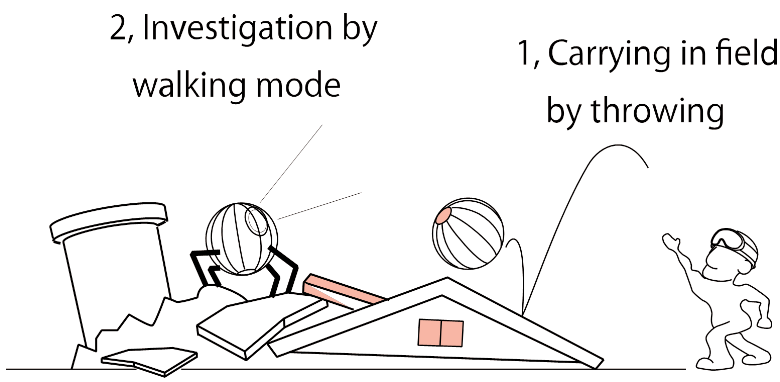

Figure 1: Application concept of our robot

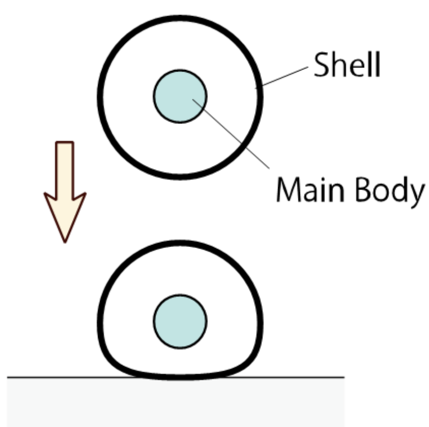

Figure 2: Spherical shell for shock-proofing.

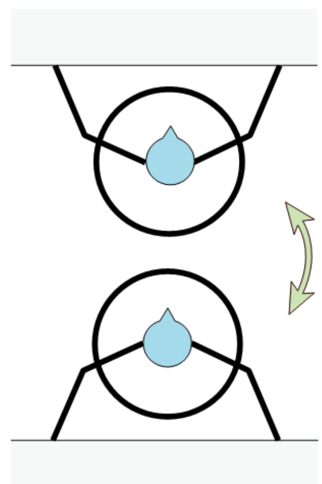

Figure 3: Omni-directional design for fall posture.

2.1 Basic Design Concept

A spherical outer shell can receive external force from all directions, such as that shown in Figure 2. It is difficult for a rectangular solid shape to absorb landing shock completely on uneven surfaces. Many mobile robots have been proposed that have a ball outer shape and can roll through movement of a C.O.G. inside the outer shell. Traveling performance of these robots,

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however, is low because reaction force of the rotating outer shell cannot be received with only the inside moment of the C.O.G. For that reason, we propose a quadruped walking robot with a spherical shell; it can change from ball mode to walking mode. With the common design of previous walking robots, because of the up and down directions, a rising mechanism is required when the robot lands upside down. We propose a new design concept that has no up and down directions. This is done by expanding the working range of each leg in the vertical direction (Figure 3).

2.2 Design of Spherical Shell

The transformable design from a ball shape to a walking mode is an old idea from ancient times. Two examples are “HARO,” a bipedal robot in Gundam, and “Destroyer droid,” a tripedal robot in Star Wars. These robots are unique mechanisms and achieving them has been difficult. The MorpHex III is a transforming Hexapod Robot that can be changed to ball mode, hexapod walking mode and rotational transfer mode by leg actuators and a body actuator (Halvorsen, 2013). However, because the ball shape is formed by the leg mechanisms, it cannot withstand external force that impacts its spherical surface. Even if it uses a structure in which the outline of the leg mechanisms can receive force, designing it to be lightweight enough for a mobile robot is difficult.

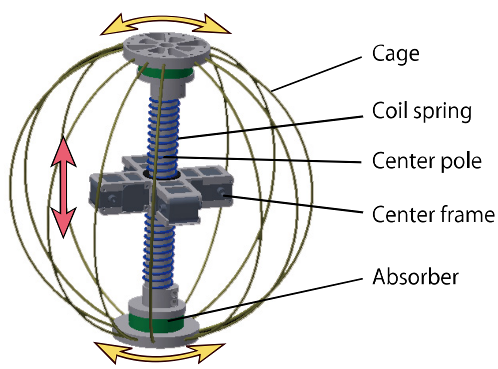

Figure 4: Structure of spherical shell of QRoSS.

We propose making the spherical outer shell and the walking mechanisms independent of each other. By doing so, our robot can achieve both functions: mobility of the legs and resistance to external shock. It can also be made small and lightweight. We designed the outer shell of the QRoSS with an outer spherical cage, rubber absorbers and a center pole with coil springs, shown in Figure 4. The cage is structured of wires featuring super elasticity. The center pole connects the outer cage through the absorbers, and the center frame, which is a base of legs, floats on the center pole over coil springs. With this structure, QRoSS can absorb external shock.

2.3 Design of leg mechanism

QRoSS's legs must be mounted between the super elasticity wires of the spherical cage. The common joint arrangement of a quadruped walking robot, which is a spider type robot, is type A of Figure 5. However, the cage prevents work space of leg motion which swings along the horizontal plane. Therefore, because the legs must swing outside the cage, type B or type C of Figure 5 can be chosen. Because both types need a large work space for the knee joint – almost 360 degrees to achieve the omni-directional design in the vertical direction and storage legs in the shell – the knees must be double-jointed. However, type C cannot store the legs in the shell and the knee and the end part of the shin are outside, as shown in the upper figure of Figure 6. This is the case because type C cannot use the inside space of the shell effectively. Type B can move the shin part into the center area using the horizontal axis of the knee joint, shown in the lower figure of Figure 6. Thus, QRoSS uses the type B joints arrangement of the leg mechanisms.

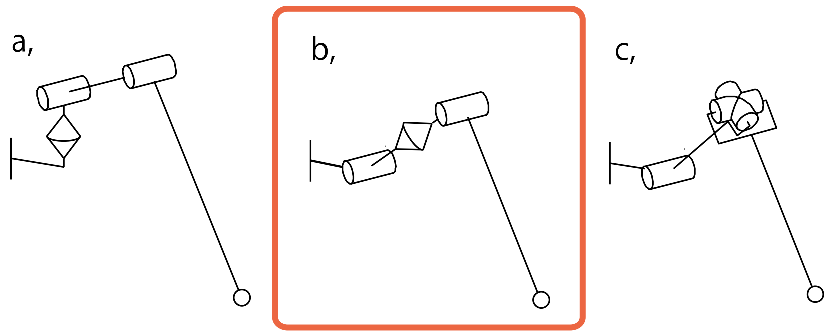

Figure 5: Arrangement of joint axes.

Jumping robot (Kovac et al., 2009) has an outer cage and can jump on two legs; the cage can absorb external forces. This robot can roll over and return to its basic posture through the center of gravity effect, which is decentered. However, it cannot use outer its outer shell to travel; it uses only its legs. The QRoSS can use the outer shell as an extra contact point and to climb over high steps.

3. Mechanical Design of QRoSS

Figure 7 is the first prototype model of the QRoSS and Table 1 lists specifications. The prototype model comprises the spherical outer shell and four legs; each leg is arranged radially from the center of the shell. Thus, the QRoSS does not have directivity in either the vertical direction or horizontal direction in preparation for landing on a complicated geographical surface.

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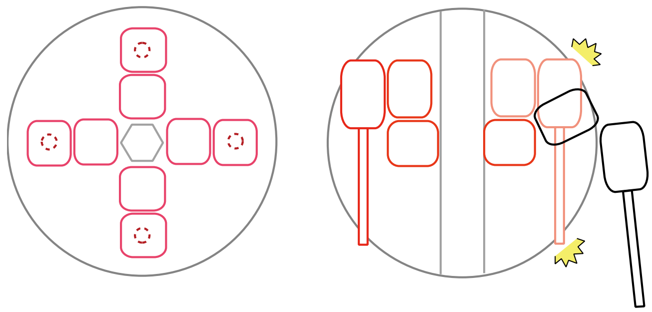
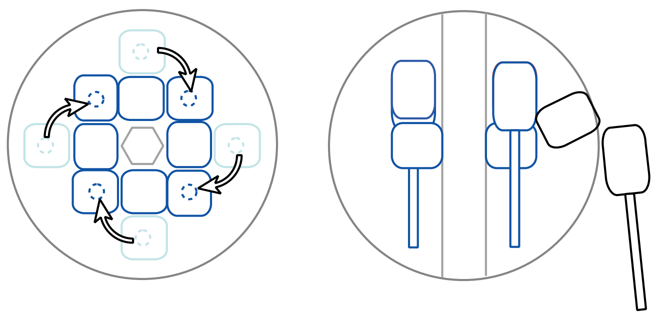
Moreover, it can move using rotation of the spherical shell. This rotational torque is bigger than that of a rotational ball robot because the legs can receive the reaction force of the shell's rotational torque. Each leg has three active DOFs: each actuator is a servo motor – a Futaba RS303MR with Maximum torque of 6.5[kgf-cm]. Battery is a Li-Fe battery (2 cells, 6.6[V], 300[mAh]); its running time approaches ten minutes.



Type C of joints arrangement: Leg structures overflows from the shell.



Type B of joints arrangement: The space in the shell can be used effectively.

Figure 6: Difference in storage states of joint arrangement of legs

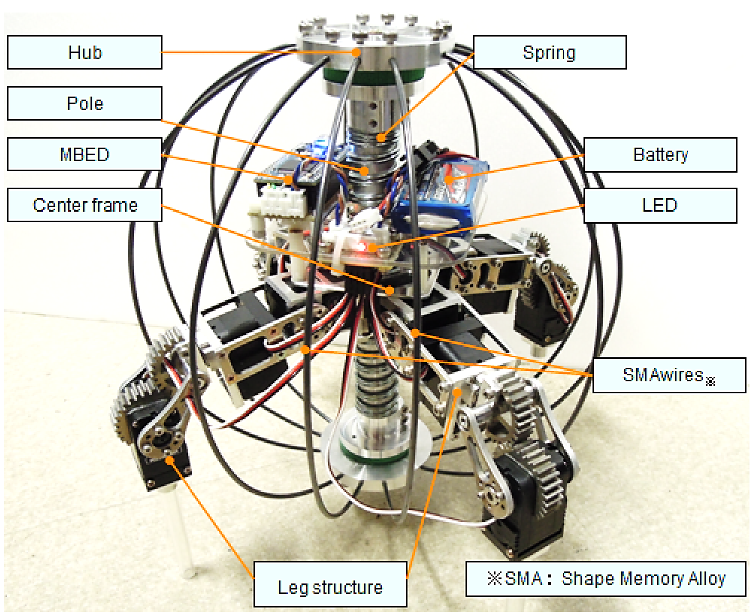
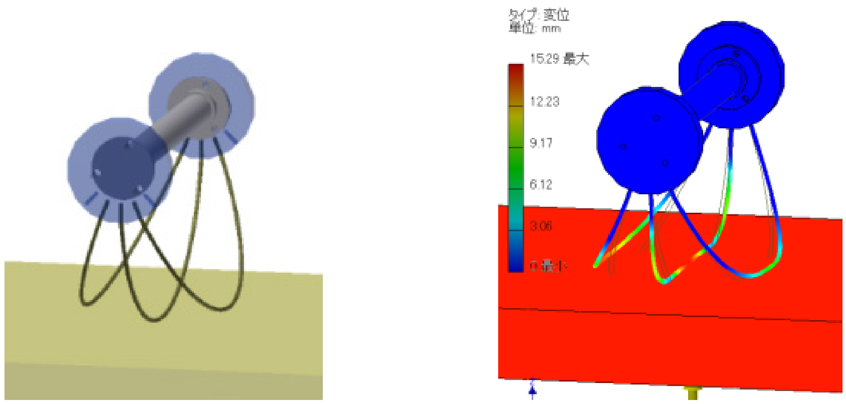


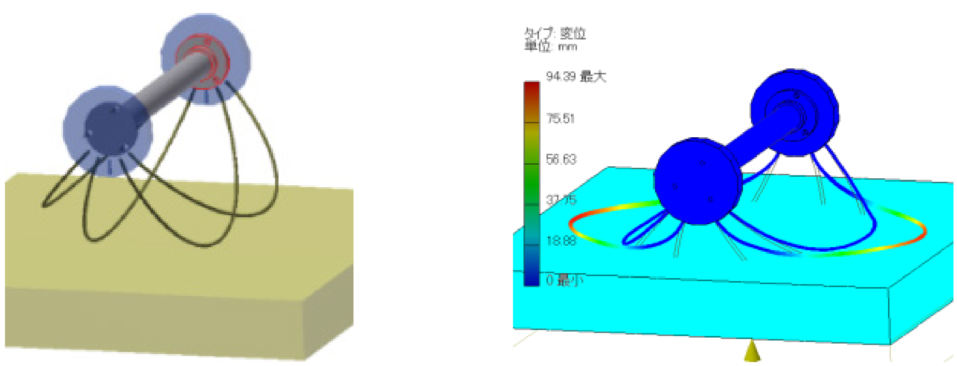
Figure 7: First prototype model of QRoSS.

Table 1: Specification of QRoSS.

Height	247[mm]
Width	240[mm]
Diameter of spherical shell	210[mm]
Mass (Including battery)	1039[g]
DOFs	12
Actuators	Futaba RS303MR
Ground clearance	40[mm]
Walking speed	140[mm/s]



Load is acted in front of a wire of the spherical outer shell



Load is acted in between wires of the spherical outer shell

Figure 8: Structural analysis of spherical shell.

3.1 Spherical Outer Shell

The outer shell is structured as a cage, which is 210[mm] diameter and comprises twelve wires, with a center pole through the absorbers. The wires of the cage are super elasticity rods – made of titanium alloys and a shape memory alloy. Therefore, when shocked from the outside, deformation does not reach the plastic region. At both ends of the super elastic rods, the amount

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of absorbable shock is small because deformations are restricted by connections to the hub. To absorb the shock in this part, the absorbers, which are made of a polyurethane foam, are arranged between the wire hub and the center pole. Because an axial direction of the center pole has no modification element (like an elastic rod) the center frame is floating, mounted on the pole by coil springs; it can slide on the surface and absorb the shock of an axial direction.

To select the wire diameter of the spherical shell, simulation of the structural analysis was performed using Autodesk Inventor. In this simulation, a static load of 800[N] was applied to the simulation model of the shell. This load is an equivalent value of an impact force: a robot's mass is set to 2[kg] and it is dropped from a height of 2[m] in free fall and an adsorption distance of 50 mm. From the analysis result, the wire diameter of the super elastic rod is set at φ2.3[mm], and 12 wires are used. This diameter is the largest size that can be purchased. The upper figure of Figure 8 illustrates receiving force from the front of a wire, and the following figure illustrates receiving force from a place where the interval of wires is the largest to expand leg mechanisms toward the exterior. Although deformation is too large when load is applied between wires, because the wire diameter is the maximum we can buy, we decided to make up for it by limiting the weight and distributing shock.

3.2 Leg Mechanism

The leg mechanisms must be designed for an up-and-down symmetrical work space and stored in the outer shell. Taking into account modification of the cage of the spherical outer shell, the clearance between the leg and the cage is prevented when the rods are modified. We therefore decided to select a double joint mechanism. The upper picture of Figure 9 is the prototype model of the leg mechanisms. Each joint is called first, second and third joint from a base joint of the body (Figure 9). At the third joint, the activity and the passivity joints can be driven as same angles by combining two gears, which have the same number of teeth, to fold the legs completely. Moreover, to be able to move the legs on the outside of the shell and prevent them from interfering with the wires of the cage when QRoSS is in walking mode, the second joint is arranged at the center of the leg to twist. Futaba RS303MRs are chosen as actuators of the leg joins; RS303MRs use serial communications and several servo motors can be operated through a single serial communication port of a micro controller. We designed the legs according to the specifications of this servo motor, in spite of its small output torque of only 6.5[kgf･cm]. Small size and the ability to use serial communication were the most important reasons for selection.

Each length of the leg mechanism is as follows: from the first joint to the passive joint of the third joint is 50[mm]; from the passivity joint to the activity of the third joint is 28[mm]; and from the activity joint to the end of the leg is 110[mm].

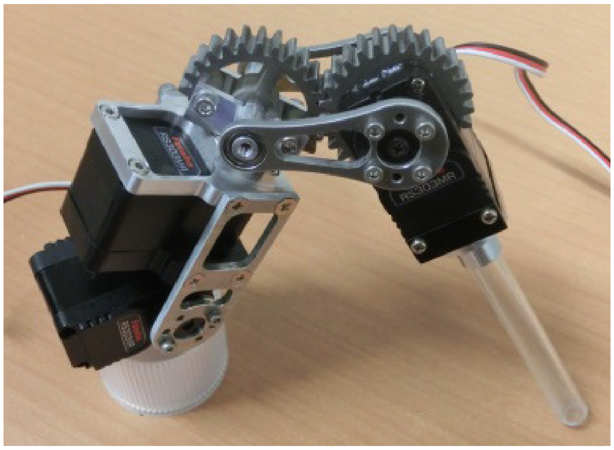
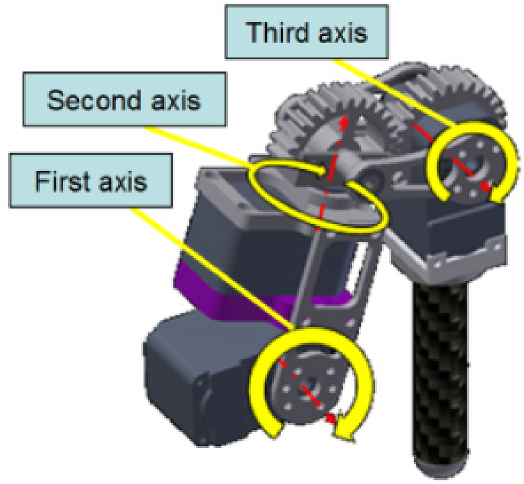
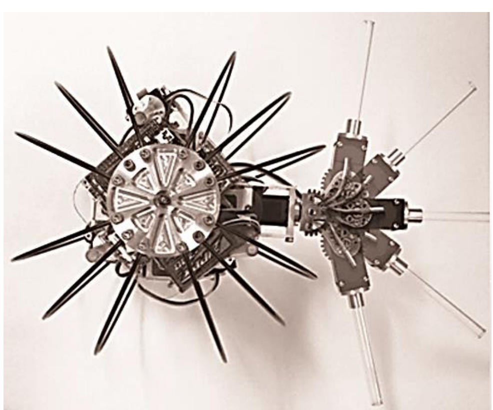
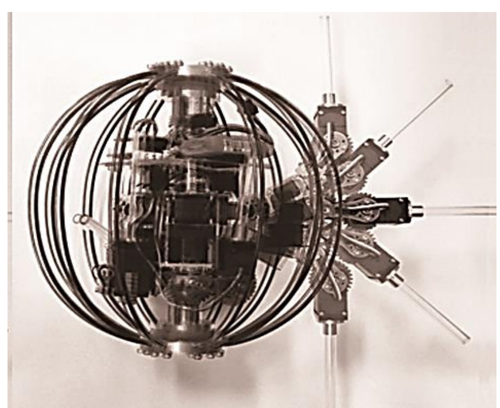



Figure 9: Prototype model of leg module.

Figure 10 shows the work ranges of the prototype is that leg mechanism. The work ranges in the vertical direction and the horizontal direction exceed 180 degrees, large enough to achieve operations. To verify the work range of the leg in walking based on the CAD model of the designed whole body, the range of the landing area of the end point of the leg, which changes with the height from the ground to the robot, was checked. Figure 11 shows the range on which the end point of the leg can land with the height of the robot. Results show that generations of walking motions are possible through planning the straight line paths required for walk operation in each circle.

Top view Side view

Figure 10: Work range of leg module.

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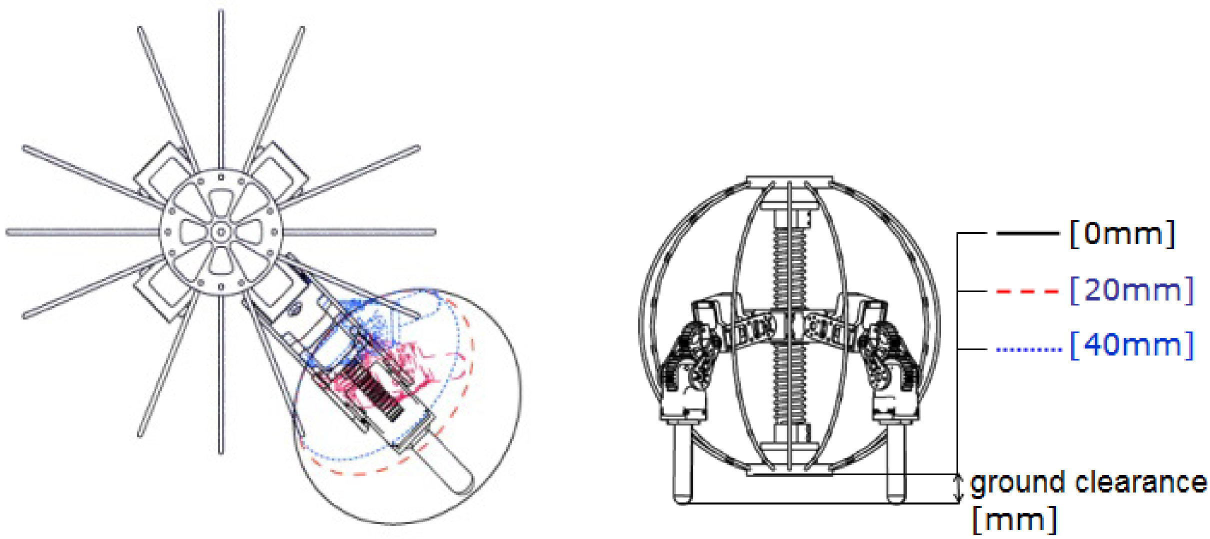


Figure 11: Results of paths of leg's end point.

3.3 System Configuration

Figure 12 shows the system configuration of the prototype model of QRoSS. We did only tele-operation because the purpose of this experimental model is to verify mobilities. QRoSS is controlled by one micro controller, the mbed NXP LPC1768 with a USB Bluetooth module. These micro controllers produce the paths of the legs and command values for servo motors of the legs and communicate using RS485 serial communication protocol. Inclination of the body is always detected by the accelerometer and the deployment direction and rising direction of the legs are controlled. The prototype model is operated from a PlayStation 3 video game pad, using wireless LAN.

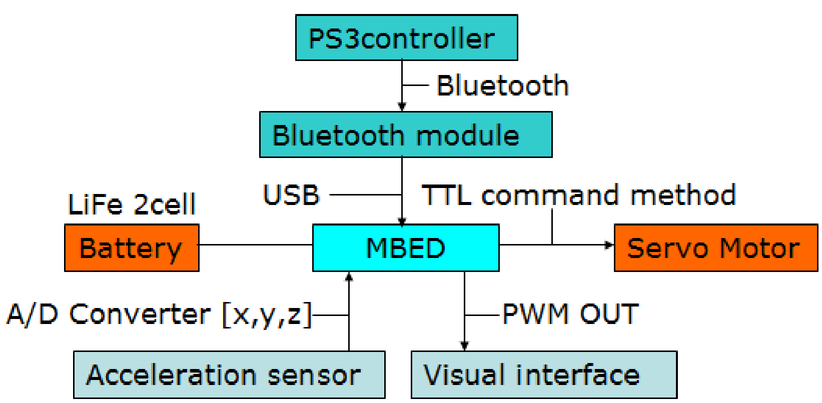


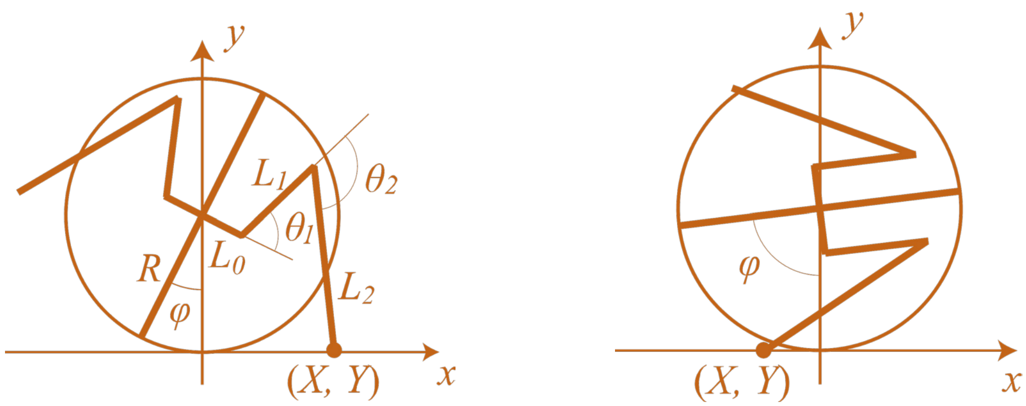
Figure 12: System configuration of prototype model.

4. Consideration of Rising Motion

The rising motion of the QRoSS is achieved by the motion path of the legs. Because it cannot detect the contact point with the ground when it lands on rubble, it needs to rise by motion of the legs from every state. We should divide and take into account rising motion and standing motion, because the actuators of the legs have only small outputs. In considering the work ranges of the legs, the QRoSS needs to perform standing operation where contact points of the foot are near the outer shell. There is no directivity in the body of the QRoSS; however, the direction in which the legs are to be folded up is decided when the legs are stored. The state in which it cannot rise by one series motion exists depending on the body posture. The left figure of **Figure 13** is a schematic illustration of the QRoSS in two-dimensional display; it is a rotational state. Where φ is an attitude angle of the body, L_0, L_1, and L_2 express each link of the leg, and θ_1 and θ_2 express the first joint and the third joint. When the grounding point of the spherical shell is the origin of *x*-*y* coordinates, the contact point of the leg is set to X and Y. If the tip of the foot has reached the ground, formulas (1) and (2) are materialized.

$$X = L_0 \cos\varphi + L_1 \cos(\theta_1 - \varphi) + L_2 \cos(\theta_2 - \theta_1 + \varphi) \quad (1)$$

$$Y = R - L_0 \sin\varphi + L_1 \sin(\theta_1 - \varphi) + L_2 \sin(\theta_2 - \theta_1 + \varphi) \quad (2)$$



Rotational state Starting state

Figure 13: Two-dimensional model of QRoSS

Although there are times when the tip of the foot may not reach the ground, the motion is not affected because the C.O.G. of the robot is at near center. If Y=0, the foot is on the ground, and x can be estimated, shown in the right figure of Figure 13. When x≥0, the QRoSS can rotate and rise in the CCW direction in a single motion. When x<0, however, by deploying the legs in the side direction of the shell, rotation is in the CW direction once, and rising occurs by slipping and closing the tip to the shell. Figure 14 is the result of estimating the border value of the rotating

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direction; the horizontal axis is φ and the vertical axis is X. The parameters are as follows: L0=40[mm], L1=50[mm], L2 =120[mm] and θ1=90[deg] whose value can be fixed near the border state. The border value is 78.7[deg]. As the graph shows, the border line is 78.7[deg], the QRoSS can rise with a single motion at the left side of the line; at the right side, however, double motions are required. Because it needs the double motions to roll over in more than half the conditions, the double motion is adopted in the rising motion.

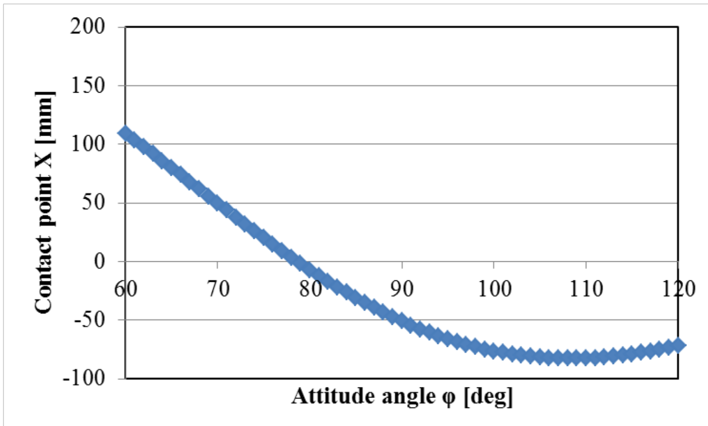

Figure 14: Rotational direction depending on attitude angle.

5. Experiments and Discussion

Three performance experiments were conducted to verify effectiveness of our design concept. In this experiment, because the current of the servo motor could not be measured correctly, quantitative evaluation was not done. Because an external power cable and wire communication would prevent mobility of the experimental robot, the experiments were made using an internal battery and wireless controller. For those experiments, the motion paths – rising motion and crawl locomotion – were prepared as the basic motion paths.

The first experiment is verification of deployment of the leg mechanism from a spherical shape and the rising operation. In deployment operation, the legs are expanded after the accelerometer detects direction of the ground when all legs are stored (No.1 of Figure 15) from No.2 to No.3: all legs are expanded from the outer shell in the horizontal direction. The posture changes into a state in which it is easy to do rising operation with four legs from the state of fall posture by this operation. In rising operation, the posture can be changed and risen through paddling motion of the leg. To reduce overload torque at the third joint, the legs once put above the landing point of the tip of the feet, as in No.4, descend to the ground verticality, and the

QRoSS finishes standing up, as in No.5. This results in confirming one series performance of rising operations.

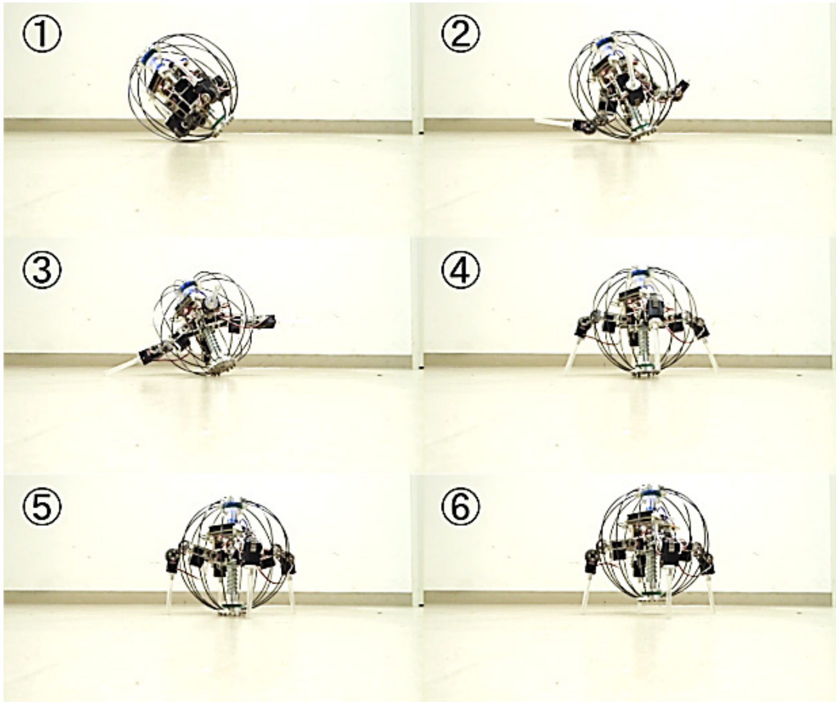

Figure 15: Deployment legs and rising

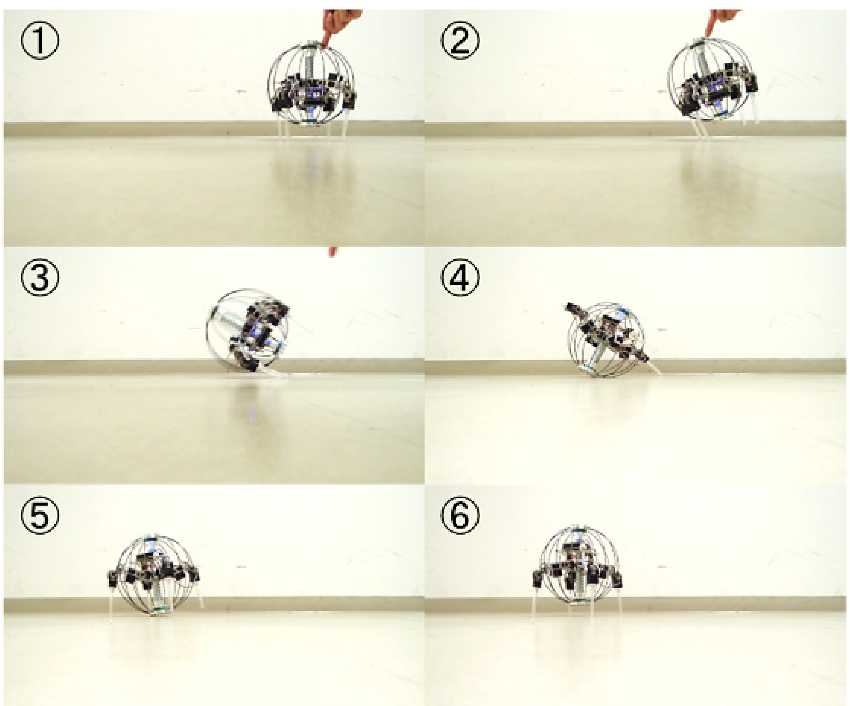

Figure 16: Return from fall state by autonomous system.

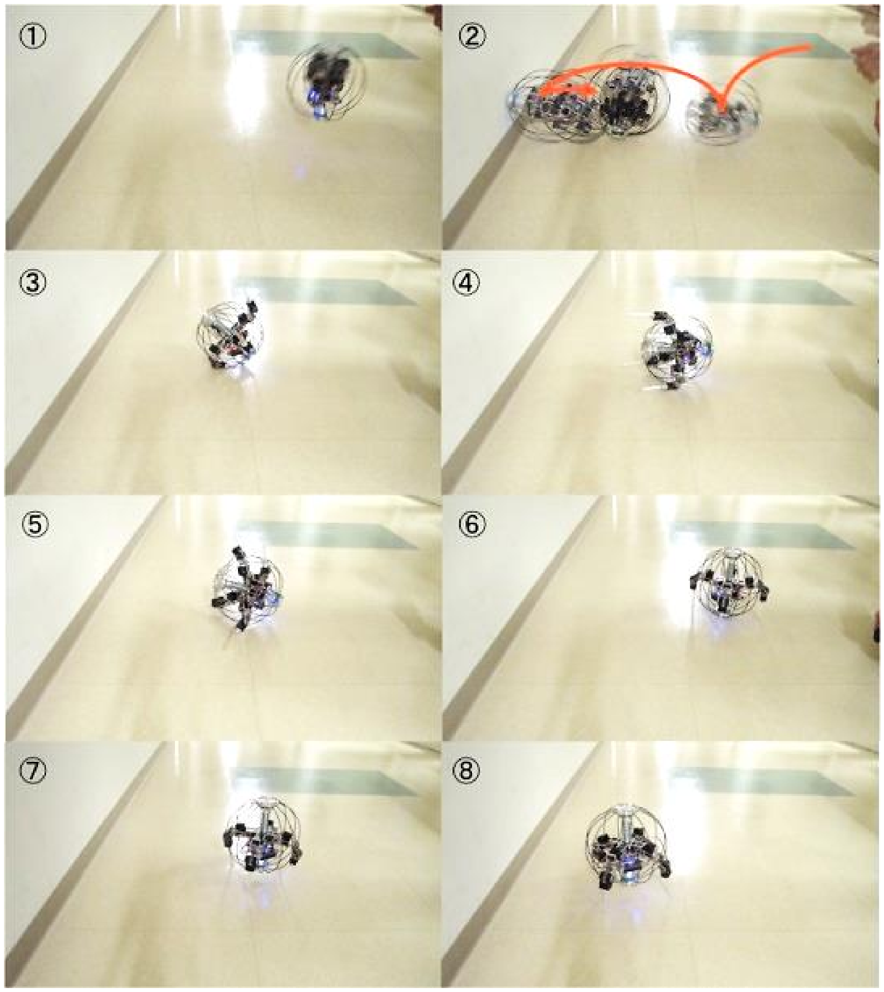

Figure 17: One series operation of rescue mission

The second experiment confirms rising operation of the autonomous system when the robot falls. Figure 16 is the result of the second experiment. Even when the posture of the QRoSS is in fall down and the reverse state, the accelerometer detected the situation, and the robot could rise by autonomous operation, confirming validity.

The third experiment confirms a series operation of the rescue missions. The following operations were performed as a series operation: throwing onto a flat surface, deployment of the legs, rising and walking, and turning by crawl locomotion. Figure 17 shows the result of the third experiment, a series of planning operations was demonstrated. In crawl locomotion of the walking mode, because the center of gravity is contained in the triangle consisting of landing points of supporting legs, stable walk is possible; maximum walking speed was 140[mm/s]. In this report, a prototype of the QRoSS was developed and validity of the design concept was confirmed. Because the return from the fall state becomes easy using a spherical outer shell, this robot can challenge travel on more difficult surfaces. However, because the first prototype model was small, large output torque of the actuators could not be analyzed and the length of the legs was restricted. Consequently, in this first prototype, locomotion has not been tested using the spherical shell. We believe that hybrid locomotion using the outer shell is an effective way of achieving mobility on uneven terrain. In future work, the second prototype model will be large enough to use actuators with sufficient output torque. And we want to demonstrate the robot at an actual disaster site and thereby prove validity.

6. Conclusion

We proposed a quadruped walking robot (QRoSS) with a spherical shell and developed a first prototype model. QRoSS is a transformable robot and can change from the storage state in which four legs are stored in the spherical shell to deploy the legs outside the shell. The shell not only absorbs external forces from all directions, but also improves mobile performance by virtue of its round shape. This paper discussed the QRoSS design concept, functional design, structural design, and arrangement of the joints. Development of the first prototype model with the structural analysis of the cage was explained. Finally, we proved effectiveness of the prototype performance through basic experiments.

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