Design of Quadruped Walking Robot with Spherical Shell

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Abstract

We propose a new quadruped walking robot with a spherical shell, named "QRoSS". QRoSS is transformable robot and can store its legs in the spherical shell. The shell is not only absorbing external forces from all directions but also improvement mobile performance by using its round shape. In rescue operations in disaster site, carrying robots is dangerous task for operators because it may cause a second accident. If QRoSS is used, carrying robots is changed to throw in and will be safe and easy. In this paper, details of design concept and developing the prototype model are reported. Basic experiments were conducted to verify its series performances which are landing, rising and walking along a rescue operation scenario.

Keywords: mechanical design, quadruped walking robot, rescue engineering

1 Introduction

Recently, many mobile robots to investigate in disaster site, where operators are difficult to enter, developed and perform rescue operations. Especially, 510 Packbot [1], which is a commercial product, and Quince [2] are performed actively as practical level use. We think that wide range searching by using many small size robots, which are for searching operation and manufactured cheaply, are very effective in order to find out victims quickly. However, carrying robots in disaster site is dangerous task, operators may be injured during carrying in by causing the second accident. If robots are able to be thrown in uneven terrain field, carrying task will be safer and easier. Various searching robots which can be thrown in for military or security use have been developed until now. The packbot 110 FirstLook, which is made by iRobot, is small type crawler vehicle with two flipper arms and can climb over the obstacles by using its arms [3]. The SandFlea, which is made by Boston Dynamics, is small wheel type vehicle and composed of four wheels and a jump mechanism. It can move and jump over high steps by gas power [4]. The Throwbot, which is made by Recon Robotics, is composed of a column body and two wheels. It can be operated by the wireless controller [5]. Each of these robots is small size, very lightweight and has shock resistance. In order that they absorb a shock by wheels or crawler belt on the ends of their body, the fall to a flat ground is satisfactory. However, the fall to a random geographical feature as rubbles of the disaster site, their body may be shocked directly. We think that their type robots need shock absorber materials which can receive external force from the all direction.

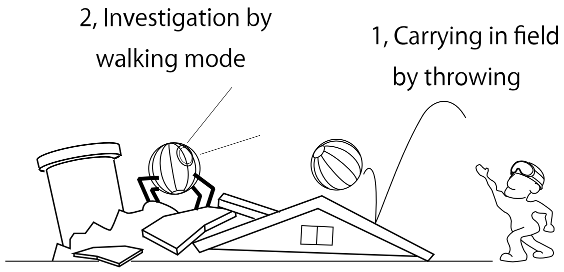


Fig. 1 Application concept of our robot

Since walking robots can contact the ground with discrete points and the contact points can be arbitrary selected according to the terrain feature. Recently, there are some robots which perform field test on uneven terrain positively. The LittleDog [6] and The BigDog [7] are famous quadruped walking robots, which are made by Boston Dynamics, were conducted the performance test of walking on the rubbles which collapse easily and a surface of a mountain. The Titan X [8] is a hybrid quadruped Walking Robot which has a mobility of the crawler vehicle. Each leg mechanism has a crawler belt which can be used also for a drive train, The Titan X demonstrates irregular ground travel performance by using a crawler mode and a walking mode properly. Almost previous works did not have the shock-proof function which protect from breakage of the body even if fall down, they were difficult to challenge walking over on irregular ground. And the kinematic performance which can return from any fall postures is required, too.

We propose and aim to develop a new design quadrupedal walking robot "QRoSS", which has a sphere outer shell and can transform a walking mode and a shock-proof mode, and report mechanical design. The remainder of this paper is organized as follows: an overview of the design concept and discussions is described in Sec. II; details of mechanical design are given Sec. III; consideration of rasing motion in Sec. IV; basic experiments and discussion are described in Sec. V.

2 Design concept

We assume the following rescue scenario as

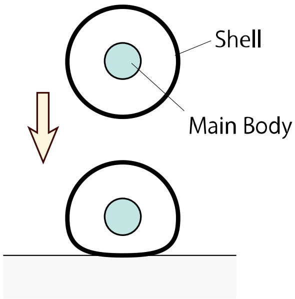


Fig. 2 Sphere shell for shock-proof

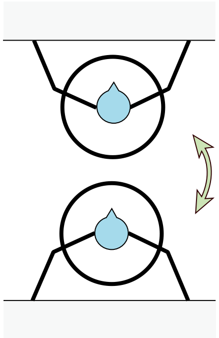


Fig. 3 Omni-directional design for fall posture

application of our robot, shown in **Fig. 1**: a) carrying investigation robot in disaster site from safety area by throwing, b) landing on the rubble while absorbing a shock, c) rising with extending legs, d) investigation by walking mode. Design requirements of QRoSS are shock absorbing, mobility and recovery.

2.1 Basic design concept

We think that a sphere type outer shell can receive external forces from all direction such as **Fig. 2**, a rectangular solid shape is difficult to absorb a landing shock completely on uneven geographical feature. Although many mobile robots, which have a ball outer shape and can roll by movement of COG in side of outer shell, have been proposed, travelling performances of same type robots are very low because reaction force of rotating outer shell cannot be received by only the inside moment of COG. Thus, we chose and proposed a quadruped walking robot with a sphere shell, it can change from a ball mode to a walking mode. In case of a common design of previous walking robots, since there is the up and down directions, the rising mechanism is required when a robot falls upside down. We propose a new design concept which is no up and down directions by expanding the work range of each leg to the vertical direction, shown in **Fig. 3**.

2.2 Design of sphere shell

Transformable design from a ball shape to a walking mode is an old idea from ancient times, for examples, “HARO”, which is in Gundam, is a bipedal walking robot and “Destroyer droid”, which is in Star wars, is a tripedal robot. These robots are very unique mechanisms but realizations have been difficult. The MorpHex III is transforming Hexapod Robot and can be change a ball mode, a hexapod walking mode and a rotational transfer mode by leg actuators and a body actuator [9]. However, since the ball shape is formed by the leg mechanisms, it cannot receive external force which acts on its sphere surface. Even if it uses structure where the outline of the leg mechanisms and receives, making light weight required for a mobile robot is difficult to design.

We propose dividing the sphere outer shell from the walking mechanisms independently. Therefore our robot can be realized both functions, the mobility of the legs and the resistance from the external shock, and may be developed small size and lightweight. We design the outer shell of the QRoSS, it is structure of an outer

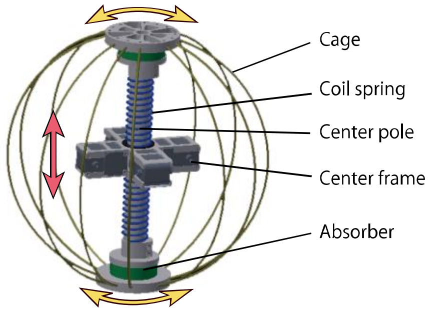


Fig. 4 Structure of sphere shell of QRoSS

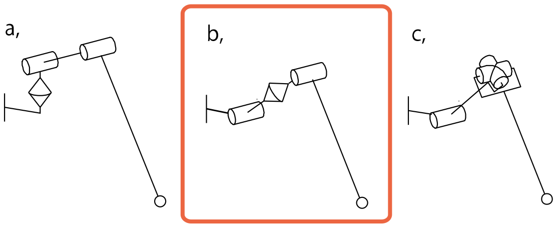
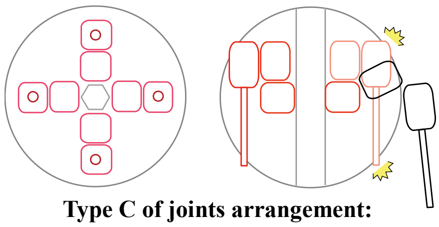
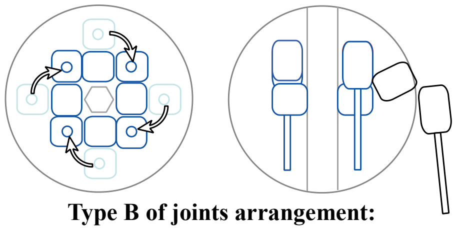


Fig. 5 Arrangement of joint axes



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.

Fig. 6 Difference in storage states of joint arrangement of legs

sphere cage, rubber absorbers and a center pole with coil springs. The cage is structured of super elasticity wires. Since the center pole connects the outer cage through the absorbers, and the center frame, which is a base of legs, is floating mounted on the center pole by the coil springs, QRoSS can absorb the external shock.

2.3 Design of leg mechanism

In case of the QRoSS, its legs have to be mounted between the super elasticity wires of the sphere cage. Common joints arrangement of a quadruped walking robot which is a spider type robot is type A of **Fig. 5**, however the cage prevents a work space of leg motion which is swing in the horizontal plane. Therefore, since the legs have to swing outside of the cage, it can choose type B or type C of **Fig. 5**. Since both type need large work space of the knee joint, almost 360 degrees, for realizing the omni-directional design about vertical direction and storage legs in the shell, the knee joint have to be double joint. However, type C cannot storage the legs in the shell and the knee and the end part of the shin are outside, shown in the upper figure of **Fig. 6**, because type C cannot use the inside space of the shell effectively. Type B can move the shin part into center area by using the horizontal axis of the knee joint, shown in the lower figure of **Fig. 6**. Thus, QRoSS is chosen type B joints arrangement of leg mechanisms.

Jumping robot [9] has an outer cage and can jump by two legs and be absorbed external forces by a cage. This robot can roll over and return to basic posture by an effect of the center of gravity which decentered. However, it cannot use own outer sell to travel, it uses only legs. The QRoSS can use outer sell as an extra contact point and climb over high steps by using it.

3 Mechanical design of QRoSS

Figure 7 is an appearance of the first prototype model of the QRoSS and **Table 1** presents the Specification of it. The prototype model is composed of the sphere outer shell and four legs, each leg is radiately arranged from the center of the shell. Thus, the QRoSS does not have directivity neither a vertical direction nor a horizontal direction in preparation for landing on complicated geographical feature. Moreover, it can move by using rotation of the sphere shell and this rotational torque is bigger than a rotational ball robot because legs can receive a reaction force of shell's rotational torque. Each leg has three active DOFs: each actuator is a servo motor, which is Futaba RS303MR and Maximum torque is 6.5[kgf·cm]. Battery is a Li-Fe battery (2 cells, 6.6[V], 300[mAh]) and its running time is almost ten minutes.

3.1 Sphere outer shell

The outer shell is structured of the cage, which is ϕ210[mm] diameter and composed of twelve wires, and the center pole through the absorbers. The wires of the cage are super elasticity rods which are titanium alloys and one of the shape memory alloys. Therefore, when shocked from the outside, its deforming does not reach to the plastic region. At the both ends of super elastic rods, their quantity of an absorbable shock is small because their deformations are restricted by connecting to the hub. Then, in order 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. Since an axial direction of the center pole did not have a modification element such as an elastic rod, the center frame is floating mounted on the pole by the coil springs, can slide on the surface of it and can be absorbed the shock of an axial direction.

In order to select the wire diameter of the sphere shell, the simulation of structural analysis was performed using the Autodesk Inventor. In this simulation, a static load which is 800[N] was acted to the simulation model of the shell. This load is an equivalent value which is an impact force: a robot's mass is set to 2[kg], it is dropped from a height of 2[m] as a free fall and an absorption distance is 50 mm. From the analysis result, the wire diameter of the super elastic rod is decided ϕ2.3[mm], and 12 wires are used. This diameter is largest size that can be purchased. The above figure of **Fig. 8** is a case of receiving force from the front of a wire, and the following figure is a case of receiving from a place where an interval of wires is the largest in order to expand leg mechanisms to the exterior. Although deformation was too large when load is acted in between wires, since the wire diameter is maximum size, we decided to correspond by a weight saving and a shock distribution.

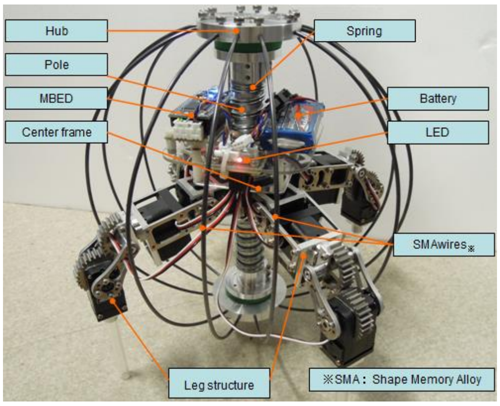
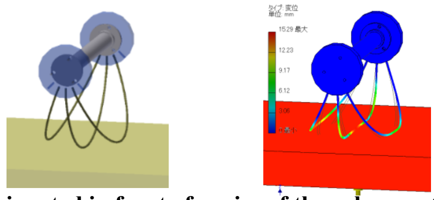


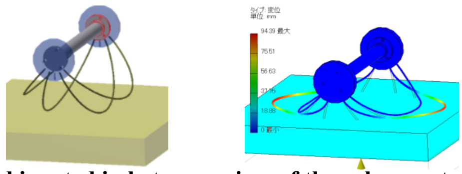
Fig. 7 First prototype model of QRoSS

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 sphere outer shell



Load is acted in between wires of the sphere outer shell

Fig. 8 Structural analysis of sphere shell

3.2 Leg mechanism

The leg mechanisms need to design up-and-down symmetrical work space and to be stored in the outer shell. In consideration of modification of the cage of the sphere outer shell, an interfering between the leg and the cage is prevented at the time of modification of the rods. Therefore, we decide to select a double joint mechanism.

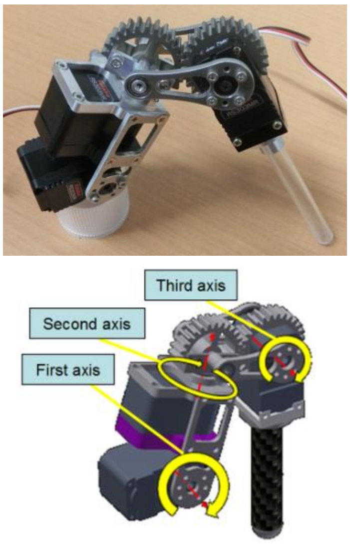
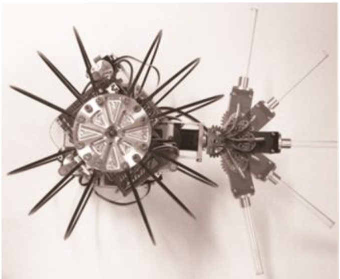
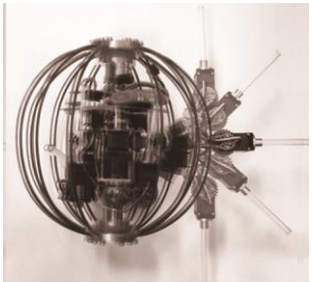


Fig. 9 Prototype model of leg module



Top view



Side view

Fig. 10 Work range of leg module

Upper picture of **Fig. 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 as shown in **Fig. 9**. At the third joint, the activity and the passivity joints can be driven as same angles by combining two gears which have same number of teeth for folding legs completely. Moreover, in order to able to be move the leg on the outside of the shell and prevent the leg interfering with the wires of the cage when QRoSS is the walking mode, the second joint is arranged center of the leg to twist. Futaba RS303MR is chosen as actuators of the joins of the legs, it can use a serial communication and several servo motors can be operated by only one serial communication port of a micro controller. We designed the legs according to the specification of this servo motor in order to have to use it in spite of the reason of a small output torque which is only 6.5[kgf·cm]. Small size and serial communication

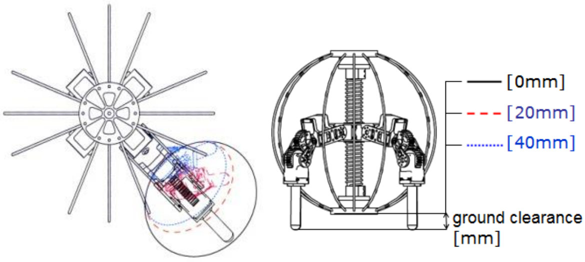


Fig. 11 Results of paths of leg's end point

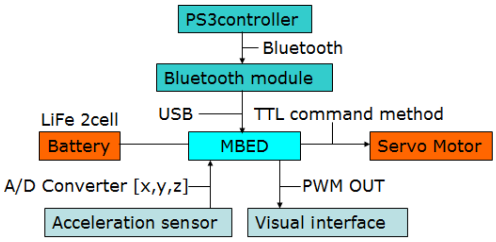


Fig. 12 System configuration of prototype model

can be used are 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].

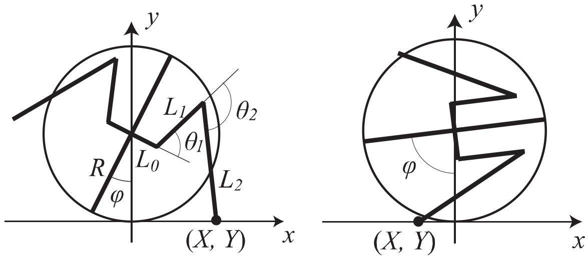
The work ranges of the prototype model of the leg mechanism are shown in **Fig. 10**. The work ranges of the vertical direction and the horizontal direction are more than 180 and are enough size to realize operations. In order to verify the work range of the leg in walking locomotion based on the CAD 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. From the results, generations of walking motions are possible enough because planning straight line paths required for walk operation in each circles

3.3 System configuration

The system configuration of the prototype model of QRoSS is shown in **Fig. 12** and we carried out only tele-operation because this model is experimental model to verify mobilities. QRoSS is controlled by one micro controller which is 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 by serial communication which is RS485 protocol. Inclination of the body is always detected by the accelerometer and the deployment direction and the rising direction of the legs are controlled. The prototype model is operated from the video game pad, which is the PlayStation 3 pad, by using wireless LAN.

4 Consideration of rising motion

The rising motion of the QRoSS is realized by the motion path of the legs. Since it cannot detect the contact point with the ground when it lands on rubbles,



Rotational state **Starting state**

Fig. 13 Two-dimensional model of QRoSS

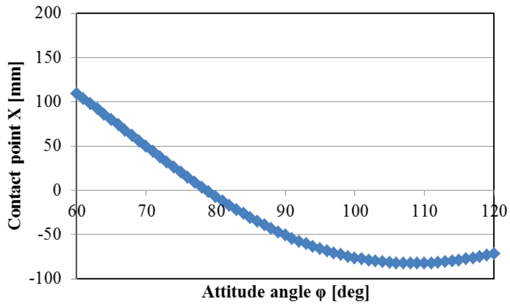


Fig. 14 Rotational direction depending on attitude angle

it needs to rise by motion of the legs from every state. We should divide and consider rising motion and standing motion because all actuators of the legs have only small outputs. Especially, in consideration of the work ranges of the leg, 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 to fold up the legs is decided when the legs is stored. Then, the state where it cannot rise by one series motion exists depending on the posture of the body. The left figure of **Fig. 13** is a schematic illustration of the QRoSS on 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 sphere shell is origin of x-y coordinates, the contact point of the leg is set to X and Y. If the tip of the foot has grounded, the formulas (1) and (2) are materialized.

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

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

Although there is a case that 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 the almost center. If Y=0, the foot is grounding, estimation of x can be conducted, shown in the right figure of **Fig. 13**. In the case of $x \geq 0$, the QRoSS is possible to rotate and to rise in the CCW direction by single motion. However, in case of $x<0$, by deployment the legs to the side direction of the shell, it rotates in the CW direction once, and rises by slipping and closing the tip to the shell. **Figure 14** is the result of estimating the border value of the rotating direction, a horizontal axis is φ and a vertical axis is X. The parameters are as follows; L_0=40[mm], L_1=50[mm], L_2 =120[mm] and θ_1=90[deg] whose value can be fixed near the border state. The border value is 78.7[deg]. From the graph, the border line is 78.7[deg], the QRoSS can rise by single motion at the left side of the line, however at the right side, double motions are required. Since it needs the double motions to roll over in the conditions more than half, the double motion is adopted in rising motion.

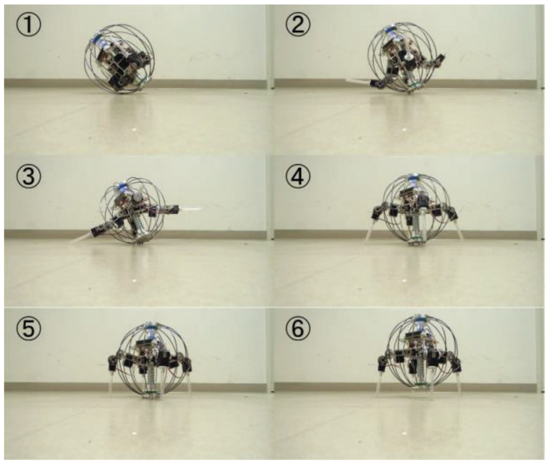


Fig. 15 Deployment legs and rising

5 Experiments and Discussion

Three performance experiments were conducted in order to verify the effectiveness of our design concept. In this experiment, since the current of the servo motor was not able to be measured correctly, quantitative evaluation has not been carried out. Since an external power cable and a wire communication are prevented the mobility of the experimental robot, those experiment were carried out by using an internal battery and the wireless controller. For those experiments, the motion paths which are a rising motion and crawl locomotion were prepared as basic motion paths.

The first experiment is verification of the deployment of the leg mechanism from a sphere shape and the rising operation. In deployment operation, legs expanding is started after the accelerometer detects the direction of the ground when all legs are stored, shown in No.1 of **Fig. 15**. From No.2 to No.3, all legs are expanded from the outer shell to the horizontal direction. The posture changes into the state of being easy to carry out rising operation by four legs from the state of fall posture by this operation. In rising operation, it can change its posture and rise by paddling motion of the leg. In order to reduce an overload torque at the third joint, the legs once put above the landing point of the tip of the feet, as No.4, they go down to the ground verticality, and the QRoSS finishes to stand up, as No.5. From the result, one series performance of rising operations was confirmed.

The second experiment is confirmed the rising operation of the autonomous system at the time of fall down. **Figure 16** is the result of the second experiment. Even when the posture of the QRoSS was fall down and the reverse state, the accelerometer detected the situation of the state, and it could rise by autonomous operation.

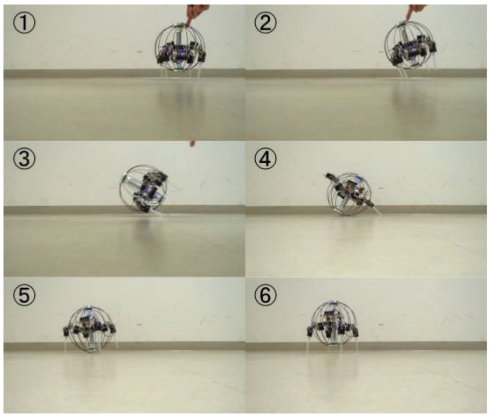


Fig. 16 Return from fall state by autonomous system

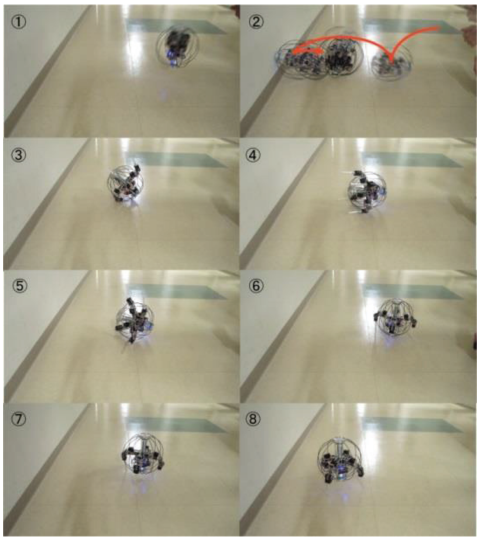


Fig. 17 One series operation of rescue mission

The third experiment is confirmed a series operation of the rescue missions. The following operations were performed as a series operation: throwing into a flat ground, deployment of the legs, rising and walking and turning by the crawl locomotion. **Figure 17** shows the result of the third experiment, a series of planning operations was demonstrated. In case of crawl locomotion of the walking mode, since the center of gravity is contained in the triangle which consists of landing points of supporting legs, the stable walk is possible, and the maximum speed of walking was 140[mm/s]. In this report, the prototype model of the QRoSS was development and the validity of the design concept was confirmed. Since the return from the fall state becomes easy by using a sphere outer shell especially, it can challenge to travel on more difficult geographical feature. However, since the first prototype model was developed small, the output torque of the actuators could not be obtained and the length of the leg had restriction. It has not performed yet realizing locomotion by using the sphere shell as the result of the first development. We think that a hybrid locomotion by using the outer shell is an effective mobile method on uneven terrain. In the future works, the second prototype model which is expanded to the large size that it can use actuators with enough output torque will be developed. And we want to demonstrate in the field where is same environment of an actual disaster site and to prove validity.

6 Conclusions

We propose quadruped walking robot with a spherical shell, named "QRoSS", and developed the first prototype model of it. QRoSS is transformable robot and can change from the storage state that four legs are stored in the spherical shell to deploy the legs to outside of the shell. The shell is not only absorbing external forces from all directions but also improvement mobile performance by using its round shape. In this paper, we discussed about the design concept of the QRoSS and decide the functional design, the structure design, and joints arrangements. The Development of the first prototype model with the structural analysis of the cage was explained. Finally, we prove the effectiveness of the performance of the prototype model from the results of the basic experiments.

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