Proceedings of the 2014 22nd International Conference on Nuclear Engineering
ICONE22
July 7-11, 2014, Prague, Czech Republic

ICONE22-30304

A Remote Operated Quadruped Robot System for Investigation of Reactor Building

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Keywords: Quadruped Robot, Fukushima Daiichi Nuclear Power Plants, Remote Control

ABSTRACT

A remote operated quadruped robot has been developed for disaster site which can move on stairs, slopes, and uneven floor under the radiation-polluted environment, such as TEPCO Fukushima Daiichi nuclear power plants [1][2].

In particular, the control method for stable walking and the remote operation system have been developed to move on stairs in the reactor building.

We applied this robot to investigation of suspicious water leakage points in reactor building at Fukushima Daiichi nuclear power plants unit2[3]. In this investigation, a small vehicle equipped with camera and a manipulator which is connected the vehicle with cable were mounted on the robot and were carried to near the target by the quadruped robot and the investigation was carried out with the small vehicle.

1. QUADRUPED ROBOT

A quadruped robot was developed for maintenance, repair and inspection of the nuclear power plant in 1980s [4]. The robot was very heavy and large in size because of its hydraulic mechanism. In recent years, the quadruped robot "Big Dog" climbing 35 degrees slope was developed [5]. This robot also uses hydraulic actuators. We used electric motors to reduce the size of the robot which can pass through the narrow aisle in the nuclear power plants and to expand the range of joint movement. The developed quadruped robot is shown in Figure 1. Each leg of this robot has two links of thigh and shin and has a joint of knee and two joints between the body and thigh link. Furthermore, the toes of this robot are spherical shape in place of flat soles to land on various floor conditions. And it is used an elastic rubber to toes in order to increase the grip force and improved the shock absorption effect at the time of its landing. Table 1 shows the specification of the developed quadruped robot. This robot can walk at maximum velocity 1km/h with 20kg payload and turn at a narrow space within 900mm. And it has a 3-axis accelerometer and a 3-axis gyro sensor to control its posture, and has 3-axis force sensors for measuring a ground reaction force while walking. It can go up to the stairs of up to 45degrees of which height 220mm. An operator can control it remotely as watching mounted 6 camera images.

2. STAIR CLIMBING

2.1 Gait

Previous works for the gait of the walking robot have been studied and summarized [6]. We adopted a trot gait with an emphasis on speed at a flat floor, and chosen a crawl gait that is more stable on the stairs.

By crawl gait, the quadruped robot is standing at three legs when one leg lifted from the ground. The only one leg lifts from the ground at a time in order that three supporting legs always formed a triangle. The quadruped robot can walk stably by keeping the center of gravity (CoG) inside the triangle. We changed a swing leg phase and a moving the CoG phase exclusively in order to walk more stably. Using above mentioned gait, the CoG is kept within the supporting triangle at all times and a landing position is correctable when the swing leg lands on the edge of the stairs.

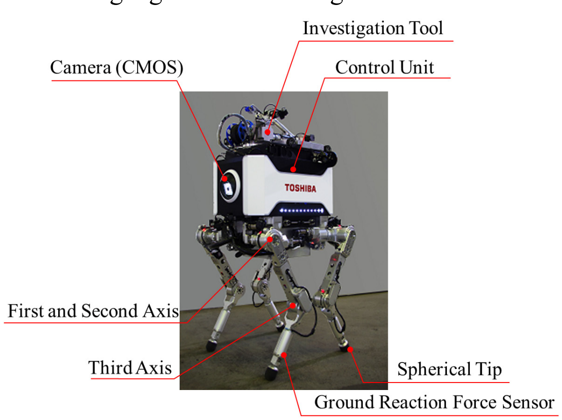


Fig. 1 Quadruped Robot

Table 1 Specification of Quadruped Robot

Size	W624 × L587 × H1066 mm
Weight	65kg
Weight Capacity	20kg
Walking Speed	1.0 km/h
Control	Wireless
Power Source	Battery, 2hours
Radiation-proof	50Gy

2.2 Control method of center of gravity

When the quadruped robot is walking on inclination and stairs, the position of the COG must control exactly since a support triangle becomes small. If it tried to keep the body level, the range which a leg can reach will be restricted by a range of movement and a link length. We controlled the posture of the quadruped robot to meet an inclination of the support triangle as shown in Figure 2.

We used a stability margin as an index value. The stability margin is calculated by the shortest distance between a side of supporting triangle and a projection point of the CoG.

The threshold value of the stability margin was set to the proportional to the height of the CoG, was taken into account the error of assembly, bending by load, and vibration of robot.

2.3 Swing leg control

Trajectories of the swing leg are shown in Figure 3. The swing leg phase consists of the following three phases.

Phase I: Lift in the vertical direction
Phase II: Move to forward direction
Phase III: Land to the ground

Phase I and phase II are divided to avoid the collision with the stairs of unknown height. In phase III, the swing leg is taken down to the same amount as the raised height.

If the landing is detected by a force sensor while go up stair, the swing leg is stopped at that position. Conversely, if the landing is not detected at the end of the trajectories, the swing leg trajectories are extended until it detects the landing. By the swing leg trajectories, the quadruped robot can walk without considering the height of the next step.

In phase I , the swing leg is temporarily lifted to the position of a few tens of millimeters, and checked the load applied to itself at the same time. If the load is remaining, the swing leg is returned to the ground position. It can prevent a turnover in advance.

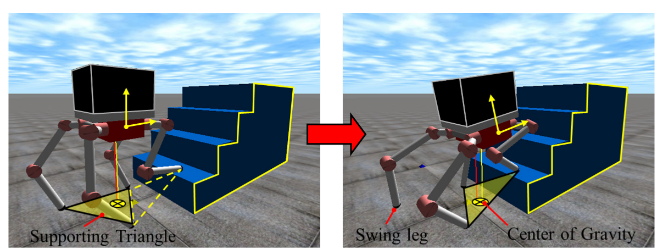


Fig. 2 Posture for Stair Climbing

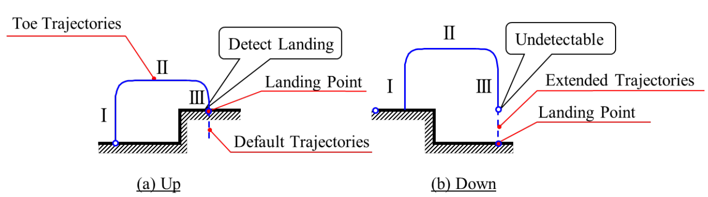


Fig. 3 Trajectories of Swing Leg

2.4 Bending direction control of leg

The developed quadruped robot is bending its knee during walking. While it is climbing stairs, there is a possibility that the knee collides with stairs. To avoid the collision, increasing the length of the leg are not advisable because of a higher level of the CoG. And increasing the number of joints easily is not also good for hardware design which should remain weights.

We have designed the movable range of the knee joint widely and to be redirected bending the knee joint.

3. REMOTE OPERATION

We operated the quadruped robot in the reactor building from another building. The remote operation system is shown in Figure.4. In the operation screen, we displayed sensing data such as temperature and the posture of the quadruped robot by CG and 6 camera images. Also we displayed a support triangle which consists of the position of the tip and the position of the CoG as a Figure. We can operate checking the size of the support triangle and stability margin. The main operating procedure is shown below.

- select the gait (trot / crawl)
- send the command (start / stop)
- send the direction of movement
  (forward / backward / left / right / rotational)
- correct the direction and the position of CoG
- correct the landing point of swing leg

Basically, the quadruped robot can walk automatically based on preset parameters such as a step size and a height of swing leg. In the actual environment, a stair size does not match the above parameter. An operator corrects the position of the landing point remotely. For example, if the swing leg landed the edge of the step as shown Figure 5, the operator can correct the landing point to the center of the step by intervention operation. At this time, the operator can use a joypad for control the leg and see 6 camera images mounted on the quadruped robot.

A waiting phase was provided at the end of a swing leg phase and a moving the CoG phase. In this phase, it is possible to move to the next phase by the instruction from the operator. The operator can secure a time to judge the situation and give instructions after the correcting motion. We realized the remote operation with less human error using by this system.

5. INVESTIGATION OF VENT PIPE

By using the developed quadruped robot, we investigated the water leakage of 8 vent pipes in the torus room which is in the reactor building at the Fukushima Daiichi nuclear power plants unit2 in 2013.

Although a catwalk is equipped on a suppression chamber in the torus room to pass at the time of periodic inspection, the vent pipe cannot be viewed directly from the catwalk that can be accessed by the quadruped robot. The flat vehicle and the arm were mounted on the quadruped robot for this investigation as shown Figure 6 and Figure 7. The specification of the flat vehicle is shown in Table 2. We used the arm to hang the flat vehicle from the quadruped robot as shown in Figure 8.

The trajectories of the quadruped robot and the flat vehicle are shown in Figure 9. The quadruped robot passed through the door and climbed stairs and walked up to 24m (one way) on the catwalk which is open grating.

The flat vehicle was run to the vicinity of the bent pipe on the suppression chamber and investigated the edge of the vent pipe sleeve and the edge of the sand cushion drain pipe and the lower part of the vent pipe bellows cover by using a camera mounted on the flat vehicle. This flat vehicle was connected by wire to the arm and the cable reel with the arm was controlled to match the movement of the vehicle.

The investigation was conducted one or two a day. The total investigation days were 18 and the total investigation time was about 300 hours including the waiting time in the reactor building. The total cumulative dose was 7.3Gy.

As an investigation result, no water leakage was founded about the all vent pipes.

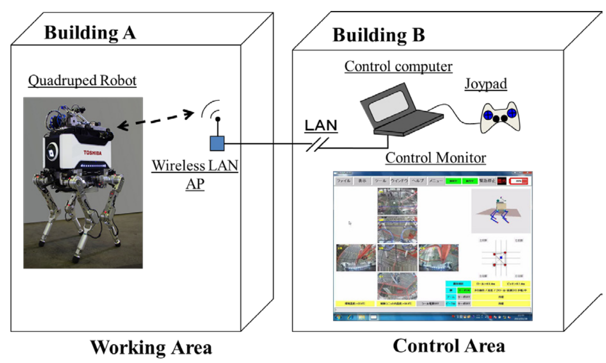
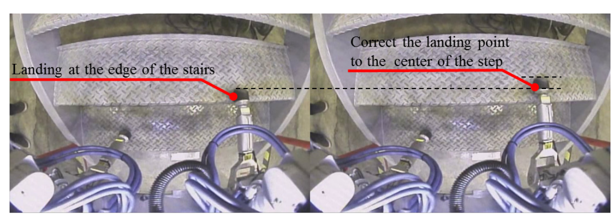


Fig. 4 Remote Operation System



(a)Automatic Operation (b)Intervention Operation

Fig. 5 Intervention Operation

Fig. 6 Flat Vehicle

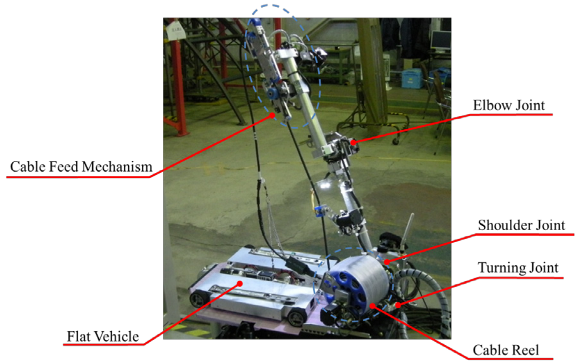


Fig. 7 Arm

Table 2 Specification of Flat Vehicle

Size	W327 × L313 × H47 mm
Weight	2kg
Speed	0.2 km/h
Control	Wired
Power Source	Battery

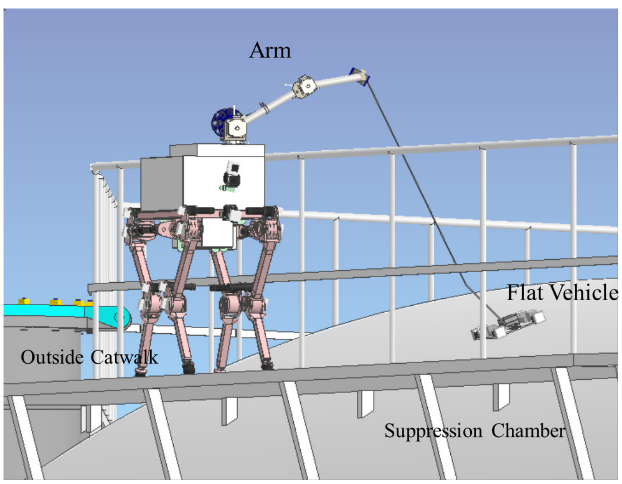
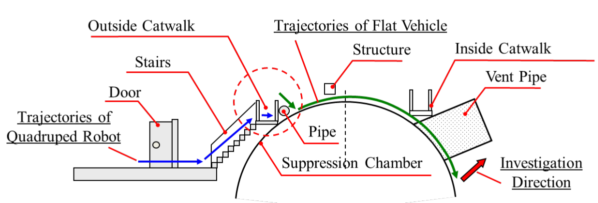


Fig. 8 Relationship between the Robot and Flat Vehicle

Fig. 9 Trajectories of Robot



6. CONCLUSIONS

We developed a remote controlled quadruped robot which can climb stairs and applied to investigation of suspicious water leakage points in reactor building at Fukushima Daiichi nuclear power plants unit2. Further work focuses on the dynamic control for walking on the rubble. And we want to apply this quadruped robot to various places as rapidly as possible.

ACKNOWLEGDGEMENTS

We are deeply grateful to persons concerned the remote technology task force for Fukushima Daiichi who provided carefully considered feedback and valuable comments.

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