



Technical Note

Development of Stable Walking Robot for Accident Condition Monitoring on Uneven Floors in a Nuclear Power Plant



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ABSTRACT

Even though the potential for an accident in nuclear power plants is very low, multiple emergency plans are necessary because the impact of such an accident to the public is enormous. One of these emergency plans involves a robotic system for investigating accidents under conditions of high radiation and contaminated air. To develop a robot suitable for operation in a nuclear power plant, we focused on eliminating the three major obstacles that challenge robots in such conditions: the disconnection of radio communication, falling on uneven floors, and loss of localization. To solve the radio problem, a Wi-Fi extender was used in radio shadow areas. To reinforce the walking, we developed two- and four-leg convertible walking, a floor adaptive foot, a roly-poly defensive falling design, and automatic standing recovery after falling methods were developed. To allow the robot to determine its location in the containment building, a bar code landmark reading method was chosen. When a severe accident occurs, this robot will be useful for accident condition monitoring. We also anticipate the robot can serve as a workman aid in a high radiation area during normal operations.

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1. Introduction

A nuclear power plant is designed to proactively shut down the nuclear reactor in a conservative manner based on the design concept of redundancy, diversity, and independence. Even though these safety designs are conservative, unexpected incidents still occasionally evolve into severe accidents. The Three Mile Island, Chernobyl, and Fukushima nuclear accidents are representative examples. While the

possibility of an accident is very low, multiple emergency plans are necessary because the impact of an accident on the public can be enormous. One of these emergency plans involves a robotic system for investigating accidents under conditions of high radiation and contaminated air.

In March 2011, a severe nuclear accident happened after a very strong earthquake of magnitude 9.0 and a 13-m tsunami impacted the Fukushima nuclear power plant. An enormous amount of radioactive particles were released at the plant site

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after fuel melted and a hydrogen explosion occurred in the reactor building, and the environmental conditions accordingly were very harsh. People expected that rescue robots would be used to investigate the plant accident under these conditions because Japan had the world's best biped walking robot at the time. However, this robot could not deal with the uneven floor of the nuclear power plant. On April 17, the Tokyo Electric Power Company (TEPCO) asked iRobot Company (Massachusetts, USA) to send a "PACKBOT" caterpillar robot and "T-Hawk" flying robots to the Fukushima nuclear plant site for accident condition monitoring [1]. Three months after the accident, the Japanese robot "Quince" was dispatched inside the plant, but failed to return.

To avoid repeating the inadvisable emergency steps used in the Fukushima nuclear accident, Korea Hydro & Nuclear Power Company (KHNP) launched a research project in January 2014 to develop an accident monitoring robot with the cooperation of the Korean Advanced Institute of Science and Technology (KAIST). The development process for the accident monitoring robot system is introduced here.

2. Nuclear plant accident

2.1. Steps in a nuclear accident

The International Atomic Energy Agency classifies international nuclear and radiological events on a scale of 0 to 7. The Fukushima nuclear accident corresponds to Number "7", a major accident. In a nuclear power plant, emergency plans include preparations for two types of accidents: design basis accidents and severe accidents. These two types of accidents are classified based on the accident's degree and probability. A design basis accident is an expected accident in the design concept. Because equipment in a nuclear power plant is qualified to survive under the harsh environmental conditions of high temperature and radiation, it is generally unlikely that a design basis accident will evolve into a severe accident. However, unanticipated events do happen, and it is possible for it to elevate to a severe accident. A severe accident is an accident that exceeds the design basis accident condition, and which consequently induces fuel melting.

2.2. Environmental conditions of accidents

The environmental conditions of accidents are dependent on the plant design type. Table 1 presents the temperature, pressure, and radiation conditions during a design basis accident and a severe accident at an APR1400 nuclear power plant [2]. Total integrated dose (TID) means 40 years normal and 1 year accident radiation exposure.

2.3. Permissible environmental conditions for a condition monitoring robot

It is not possible to access the containment building of a nuclear power plant during a design basis accident because the temperature, pressure, and radiation levels are too high. When the pressure of the containment building is higher than normal because of an accident, opening the personnel hatch is not allowed. Consequently, a robot cannot be put into the containment building for accident condition monitoring. The same situation also applies for a severe accident. A robot can be sent into the containment building after the temperature falls below 60°C and the pressure reaches that of the atmosphere. This temperature was decided based on a literature survey of temperature endurance for the parts used in the robot. It was verified that the CPU of a computer is the weakest part in terms of withstanding temperature. An Electric Power Research Institute (EPRI) document states that radiation tolerance levels for metal oxide semiconductor integrated circuit (IC) families range from about 10 Gy for commercial circuits [3]. Because this robot uses an IC system, it can survive until the total radiation dose reaches 10 Gy. Considering that the radiation exposure at the Fukushima site after the accident was 0.2–300 mSv/h [4] and the permissible dose for a worker is 50 mSv/y, it is clearly understandable why accident condition monitoring by a robotic system is indispensable.

3. Development of the accident condition monitoring robot

3.1. Requirement of accident condition monitoring robot

There are three essential requirements for a robot system to be able to successfully perform accident condition monitoring: (1) Wireless data communication between the robot and a remote controller should not be disconnected when the robot moves around inside of the containment building. It has to be assumed that concrete walls may interrupt radio wave signals. (2) The robot should be stable when walking on an uneven floor, such as gratings and stairs. The robot should easily recover a standing position if it falls down because of an obstacle on the uneven floor. (3) The robot should recognize its position under conditions when no GPS (Global Positioning System) signal is available.

3.2. Wireless data communication

A containment building consists of several rooms. These rooms are constructed with thick concrete walls for protection from high radiation from the reactor, steam generator, reactor

Table 1 – Environmental conditions of an APR1400 accident.

Description	Temperature (°C)	Pressure (psig)	Radiation TID (Gy)
Design basis accident	Peak 182/236 sec and 182–61/1 yr	Peak 60/2,000 sec	2×10^6
Severe accident	Peak 623/10 sec and 187/72 hr	Peak 60/2,000 sec	2×10^6
TID, total integrated dose.			

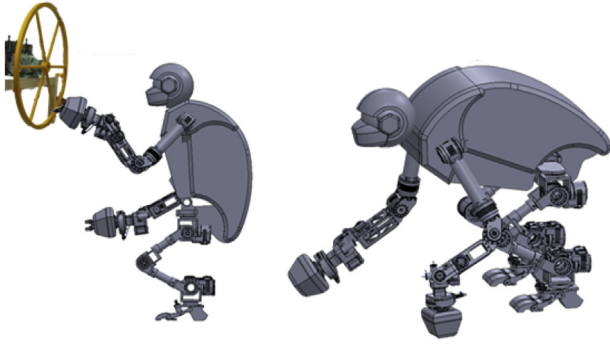


Fig. 1 – Two-leg and four-leg walking.

coolant pump, and pressurizer. When an accident monitoring robot enters this concrete room, Wi-Fi radio signals from outside will be interrupted by the thick wall. This results in the failure of remote control. Radio relay using a Wi-Fi extender is a possible solution. The Wi-Fi extender can be carried by a remote control drone. In this scenario, several drone systems will fly and land in appropriate places to relay the remote control data. Because the radio relay is conducted among the remote control center, the Wi-Fi extender of the drone, and the walking robot, radio does not have to reach a room where the robot cannot walk in because of a closed wall. According to our experiment, a 2.4-GHz Wi-Fi relay was possible through a 50-cm open space of a wall. Because permanent installation of a Wi-Fi relay system is not allowed in the nuclear power plant, dispatch of a flying drone into the containment building is a suitable alternative.

3.3. Stable walking on uneven floor

Because a nuclear power plant is designed for human movement, some hallways are as narrow as the width of a man's shoulder and some floors consist of raised spots, slopes, or stairs. It seems reasonable to expect that a biped walking design would be suitable for a condition monitoring robot. However, biped walking has a weakness. Because the robot is

not capable of quickly balancing, as a human can, it often fails to balance its weight if the floor is not flat, and in such cases, the robot will fall down. The falling impact can damage the robot's system and if the damage is serious enough, the robot may not be able to recover to a standing position, and the accident condition monitoring mission will fail. Previous studies have reported that unsteady biped walking leads to difficulty in walking on rough roads and outside land. On the contrary, quadruped robots and multiple legged robots can walk on outside rough roads [5]. A walking robot is stable when its center of gravity lies inside of the robot's support polygon. The area of the support polygon for biped walking is generally much smaller than that of a quadruped. For this reason, a quadruped gait is more suitable for stability on uneven ground.

To compensate for the weakness of biped walking, we designed a two- and four-leg convertible walking robot. Two legs are used for two-legged walking. The two legs and the two arms are both used for walking on four legs, as shown in Fig. 1. The robot pelvis will expand for the four-leg walking configuration, as shown in Fig. 2. Whereas two-leg walking is useful for a narrow and flat hallway, the four-leg walking configuration is better for stable walking on an uneven floor.

From the results of several experiments for robot walking, it was found that quick weight balancing was difficult for a robot when the floor angle changed slightly from 0° to 2° . We decided to develop a ground adapting foot for weight balancing at such a small angle change. Fig. 3 shows the structure of the floor angle adapting foot. A force/torque sensor measures vertical force (F_z) and twist moment (M_x, M_y). x_{zmp} and y_{zmp} can be calculated by dividing M_y , M_x by F_z . Based on the calculation results of F_z and x_{zmp} , a valve open or close action to adapt to the floor condition will be performed. Figs. 4 and 5 show the valve open/close algorithm and foot active control mechanism based on zero moment position (ZMP) location.

Even if we reduce the possibility of a robot falling by using the two- and four-leg walking configuration and the floor adapting foot, there is still a possibility of falling due to unknown conditions. It is therefore necessary to prepare a plan for recovering the robot to a standing position from a lying

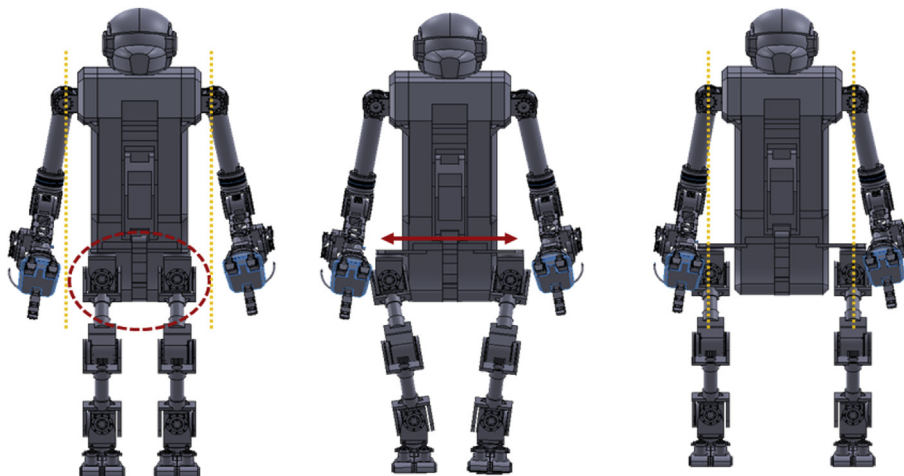


Fig. 2 – Transforming the robot pelvis for two- and four-leg walking.

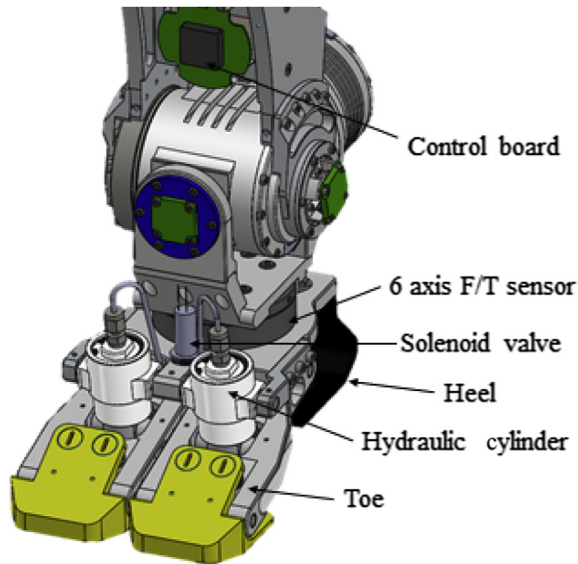


Fig. 3 – Structure of floor angle adapting foot.

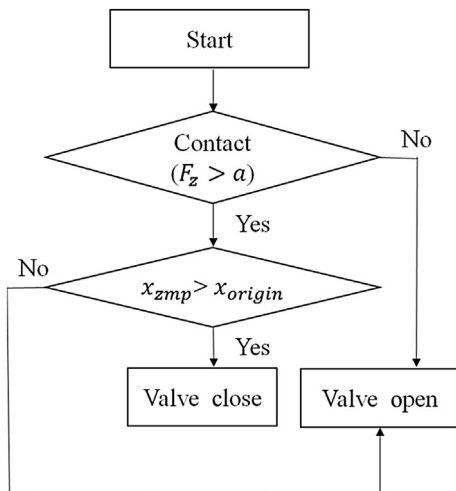


Fig. 4 – Valve open/close algorithm.

position. The robot should also be robust against a falling impact. When a robot loses its weight balance for an unknown reason, the robot body may fall down suddenly. Weight balancing is impossible in such a short time. To address this situation, we designed a defensive falling method. Because the back part of the robot's body is slightly heavier than its front, the robot easily falls down in the rearward direction. The rounded design of the back part of the body allows the robot to roll like a roly-poly. Because the robot body is composed of a carbon fiber reinforced plastic (CFRP), which has good strength and impact absorption, the falling impact does not produce severe damage to the robot system. The robot can recover to a standing position by using its two arms and two legs. Fig. 6 shows images of the robot recovering stage simulated by a “webots simulator.” The green color block is the support polygon, and the red cross sign is the center of mass (CoM). In the case of static walking, the ZMP is the same as the CoM projection, and the CoM is safe if it is located in the green color block. When the robot loses its balance, it immediately folds its knee to lower the weight center, which consequently mitigates the falling impact. For standing from a lying position, the upper body folds toward the front and quick hand pushing to the floor after folding the legs folding is performed. When the center of weight reaches the foot area, the robot can stand up by using its ankles and knees.

3.4. Localization of robot without GPS

The remote control of the robot mainly relies on the visual information provided by the robot's camera. If the robot moves to several positions within the containment building, the robot may not recognize its present position and retreat path. As previously noted, because of the thick outer concrete wall of the containment building, a GPS signal cannot reach the inside of the containment building. Because of this GPS interruption, an alternative localization methodology had to be devised. The RSSI (received signal strength intensity/indicator) and TDOA (time difference of alive) methodologies were suggested as alternatives to GPS. They were both discarded, however, because of measurement deviation and device installation problems. SLAM (Simultaneous Localization and Mapping) was also considered [6]. Discriminating a walking path in an environment with complicated equipment, cables,

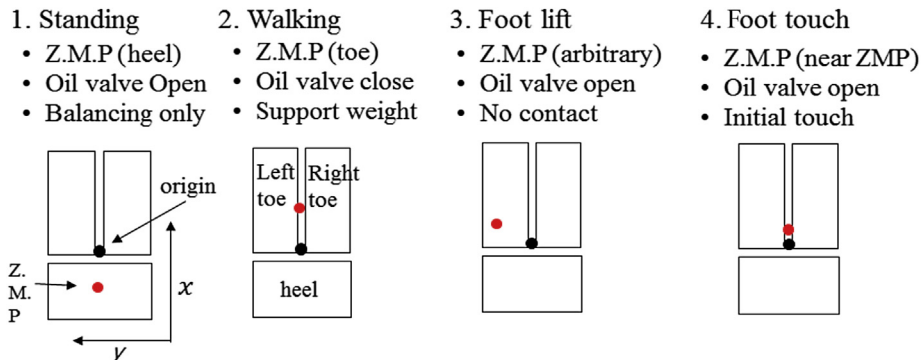


Fig. 5 – Foot active control mechanism based on ZMP location. ZMP, zero moment position.

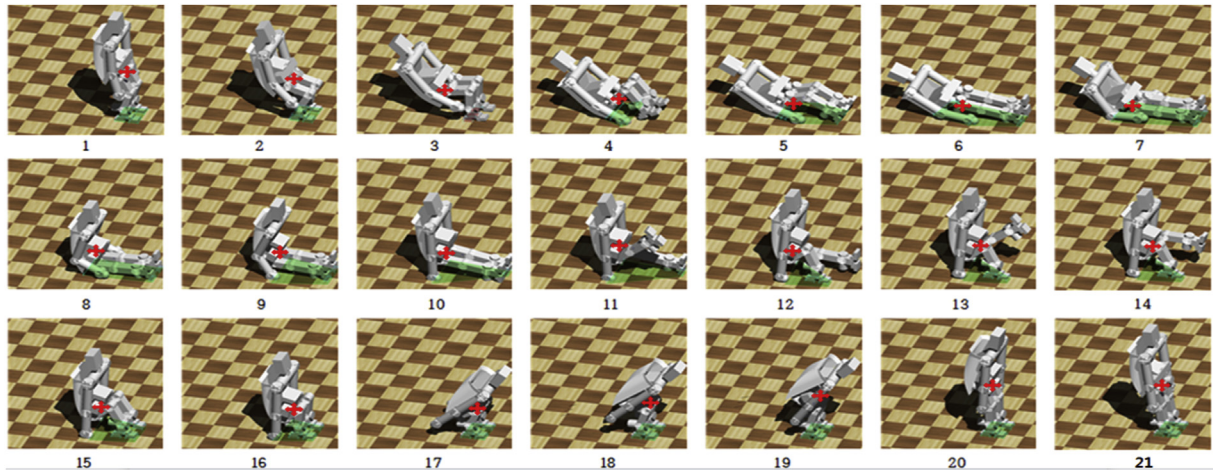


Fig. 6 – Stages of robot recovering.

Table 2 – Evaluation of landmark types.

Landmarks	Discrimination at every direction	Cognition at long distance	No power	Sensitivity to light intensity
Character and numerals	×	○	○	○
Color classification	○	○	○	×
Active RFID tag	○	○	×	○
Passive RFID tag	○	×	○	○
QR code	×	○	○	○
Bar code	○	○	○	○

○, good; ×, bad.
QR, quick response; RFID, radio frequency identification.

and structures involves challenging work for SLAM. We thus needed to find a more cost-effective methodology.

Landmark localization is a cost-effective method because it uses vision only. In this approach, the robot recognizes its

position by looking at landmarks on the containment wall [7]. Following an evaluation of several types of landmarks, a bar code was finally selected as the most effective approach, as shown in Table 2. To conduct a landmark reading test, we

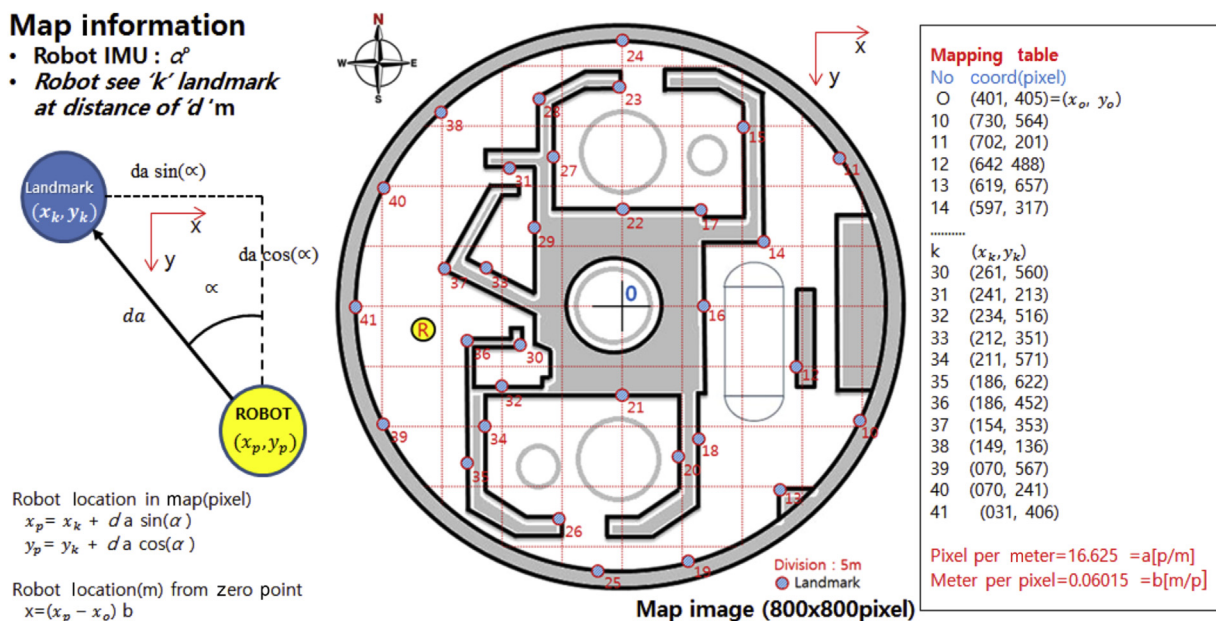


Fig. 7 – Calculation method of robot location in map.

installed 300×500 -mm-sized bar codes on a wall. Each bar code was prepared after converting a decimal area number to binary code. To ensure the bar code could be clearly read at long distance and in low light, the EAN (European article number) and the parity checking method were combined.

For calculation of the robot location, a mapping table, the yaw value of the inertial measurement unit (IMU), and the distance between the robot and a landmark were used, as shown in Fig. 7. Landmark positions and a map of the containment building were prepared based on a two-loop reactor plant in Korea.

As a result of conducting bar code reading tests at several distances, it was verified that at 11 m distance, the image reading was slightly unstable. A test to confirm clear reading at 0° , 15° , 30° , and 45° horizontal angles was also performed. From the results of these tests, it was verified that the horizontal angle view did not influence the bar code reading. Bar code reading was possible regardless of whether the wall was flat, round, or square.

4. Conclusion

KHNP has developed a robot for accident condition monitoring in nuclear power plants. To develop a robot that is suitable for operation in a nuclear power plant, we focused on eliminating the three major obstacles that challenge robots in such conditions: the disconnection of radio communication, falling on uneven floors, and loss of localization. To solve the radio problem, a Wi-Fi extender was used in radio shadow areas. To reinforce the walking, we developed two- and four-leg convertible walking, a floor adaptive foot, and a roly-poly defensive falling design. Automatic standing recovery after a fall was also developed. To allow the robot to determine its location in the containment building, a bar code landmark reading method was chosen. To carry the Wi-

Fi extender in the containment building, a drone system equipped with collision protection will be developed independently.

It is our hope that a severe accident will never happen again. Nevertheless, if such an accident occurs, this robot system will be useful for accident condition monitoring. We also anticipate that the robot can serve as a worker aid in high radiation areas during normal operations of a nuclear power plant.

Conflicts of interest

The researcher claims no conflicts of interest.

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