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Consideration of Task Performance for Robots Engaged in Extremely Dangerous Environment in Nuclear Power Plants

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1. Introduction

After Fukushima Daiichi Nuclear Accident, it is started to pay more attention to operation and accident of nuclear power plants (NPPs). For domestic nuclear industry, it was recommended to establish corresponding strategies against accidents due to extremely dangerous natural disasters [1]. Each nuclear power plant is also preparing to establish strategies to secure nuclear safety functions by estimating the counterplans for extreme accidents [2]. Robots are particularly being used to access the areas where those are dangerous for human beings to access or to restore the accident. Robot technologies in NPPs are emerging cutting-edge technologies that are just a start except the developed countries like USA, Japan, etc. But they are carefully considered because they have the advantages of performing tasks in extremely dangerous environment in NPPs instead of human beings.

In this study, the applicability of robots will be considered in extremely dangerous environment in NPPs.

2. Selection of Extreme Conditions in NPP

Disasters which can affect the safety of nuclear facility can be broken into two parts, natural disasters and manmade accidents, and combinations of both may also occur. The last resort for safety assurance of nuclear facility is maintaining critical safety functions, and it is necessary to define the extreme conditions which can influence on the nuclear facility safety to this limit. Extreme disasters are defined as disasters which occur in the extreme conditions.

To determine the extreme condition of the disaster which can influence on the nuclear facility safety, meaningful statistics are required for each disaster. But the period in which statistics data can be handled is limited, and consequently large scale disasters that can be occurred but not expected can be omitted in statistics data. Therefore, disasters that have high uncertainty or difficulty to secure meaningful statistics data have no choice but to take conservative conditions deterministically. In this sense, two ways to define extreme conditions are considered; a probabilistic method which builds a probabilistic model using statistic data and selects the condition which has low occurrence frequency conservatively as an extreme condition, and a deterministic method which selects the conservative condition, if possible, as an extreme condition because it is difficult to secure statistics data.

Disasters which can affect the nuclear facility safety and also are applicable to domestic NPPs, are natural disasters from earthquake, tsunami (seismic sea wave), strong wind, flood, snowfall, lightning and artificial accidents from airborne collision, fire, and explosion. Also combinations of these disasters can be occurred according to the causal relationship.

Selection guidelines of extreme disasters applicable to domestic NPPs are as follows;

a. Earthquake: happening frequency 10^{-4}/y
b. Seismic sea wave: happening frequency 10^{-4}/y
c. Storm surge: happening frequency 10^{-4}/y
d. Flood: happening frequency 10^{-4}/y
e. Strong wind, snowfall etc.
f. Airborne collision
g. Wide area fire and explosion (multi-unit co-occurrence)

When a beyond-design-basis earthquake hits, fires can occur at various areas in multi-unit, but the prediction of the fire area is difficult practically. And the plant fire protection system is designed for a single unit and a single fire, thus critical management functions of NPPs can be lost with a high probability when fires occur in the wide area of the plant by earthquake.

3. Technology Trends of Robots Engaged in Extremely Dangerous Environment in NPPs

When harsh environments are occurred with collapse of the building or high radiation exposure due to the extreme conditions occurrence by a natural disaster in NPPs, robots can be used for access to the area where human beings cannot access and restoration works. Although robot technology is an emergent technology with very short research and development history and it stays at the very beginning stage except some advanced country like USA, Japan, etc., it is carefully considered because of the advantage that it carries out difficult tasks in harsh environment on behalf of human beings.

Table 1. Technical capabilities needed for events in the disaster response scenario [3]

	Autonomy - Perception	Autonomy – Decision-Making	Mounted Mobility	Dismounted Mobility	Dexterity	Strength	Endurance
Drive utility vehicle to site	X	X	X		X		
Travel dismounted across rubble	X			X			X
Remove debris blocking entryway	X			X	X	X	X
Open door, enter building	X			X	X		X
Climb industrial ladder, traverse industrial walkway	X			X			X
Use tool to break through concrete panel	X	X			X	X	X
Locate and close valve near leaking pipe	X	X		X	X	X	X
Replace component	X	X			X		

Table 2. Characteristics of robots engaged in extremely dangerous environment in the NPP for each country

Nation	Robot	Characteristics
Japan	Moni-Robo	0.8×1.5×1.5m/600kg, Max speed 40m/min Wireless control from a distance of up to about three quarters of a mile (1.1km), radiation detect, 3D camera, Temp. and Humidity sensor, dust sample collect, flammable gas identification sensor
	Quince	655×481×225mm/26.4kg, Max speed 1.6m/s Camera, mic, location, PSD, laser distance detector, WiFi, infrared ray heat camera, CO sensor, 3D calculation of object or space, remote control robotic arm Appling to Fukushima Daiichi Accident site
	ACM-R5	Snake type, Module size: 80mm×170mm, Total length: 1.75m for 9 modules, Weight 800g/module (7.95kg for 9 modules) Video camera, wireless control
	HAL	Robotic exoskeleton
	MAR-C	Carrying out or valve open and close, 15^{o} slope, 220mm height step progress is possible
	MEISTeR	Radiation resistant robot, 50^{o} slope, 220mm height step progress is possible, suction of radiation material and removing polluted wall, carrying independent tasks at the same time (~15kg for each arm), wire and wireless communication, external power, self-contained battery(2hr)
	Robot	Detection of leak source which put the decommissioning task to bother
	High-Access Survey Robot	Checking Fukushima Daiichi reactor internal
USA	Pack Bot	Max(88.9×52.1×17.8cm)/Min(68.6×40.6×17.8cm), Max speed 5.8 mph/10.89kg Radiation level inspection and 3D pollution mapping data transmission at Fukushima
	Warrior	Max(105.5×76.7×75.7cm)/Min(88.9×54.1×45.7cm), Max speed 12.9 km/h / 68kg
	Dragon Runner	38×30×13cm, Max speed 70 km/h / 4kg
	Snake Robot	Diameter 5cm, length 97cm, Camera, LED Underwater activity, connected 16 nodes and moving like snake
	Cannonball	NPP coolant pipe inside swimming, application of 3D print technology
Germany	SUSI	NPP primary coolant pipe inside swimming Remote control, direct observation of reactor with camera and ultrasonic sensor

Because NPPs are operated and managed by trained people, moreover because of geographical, structural characteristics, the roles of robots developed for special purpose are very limited. Especially it was known that a few countries like Japan and USA which wanted to put robots into the site to control the Fukushima Daiichi Accident had difficulties at the beginning of the accident due to complex geometry and high radiation environment.

DARPA (US Defense Advanced Research Projects Agency) affiliated organization of Department of Defense opened the DRC (DARPA Robotics Challenge) to attract development of robots which can be used in extremely dangerous environment and to respond against the extreme conditions as Fukushima Daiichi Accident, designating technical capabilities needed for events in the disaster response scenario (Table-1). But, for more practical and effective R&D, geometric and structural characteristics of NPPs should be considered and applied carefully. Moreover, it is known that collaboration with space technology like cosmic radiation shielding technology will be needed to protect the electronic circuit of robots which has a risk of damage by high radiation exposure.

For such reasons as mentioned, in case of development of robots that will be operated for NPPs in extreme conditions, it is needed to consider not only robotics technology but also understanding of nuclear events. Consequently, understanding about robots which are already developed and applied to the field and establishing of details which should be applied to robots that will be operated in extreme conditions will be helpful not only to robot development which is needed for response of nuclear events, but also to smooth problem solving in NPP extreme conditions.

Figure 1 and Table 2 show robots engaged in extremely dangerous environment in the NPP for each country and those characteristics.

4. Execution of Missions in Extreme Conditions in NPP

After the accident, robots can be deployed to take the suitable action or respond against the event. In case of PHWR, it can be considered that robot is used to open MSSV manually in case of fire situation because the fire may prevent plant operators from getting close to the MSSV area. For PWR, robot can be used for connection of safety-related instrument air system for operation of SG PORVs and auxiliary feedwater flow control in MCR, connection of mobile diesel generator before discharge of load shedding battery, operation of a charging pump after opening of charging pump room doors, and operation of residual heat removal system after connection of mobile sea water pump.

In this manner, tasks that require human being operator actions can be substituted to robot performance.

5. Discussions

To secure critical safety function in extreme disaster conditions for domestic NPPs, operator manual actions or main tasks of robots are as follows;

- Opening of MSSV and ECCS isolation valve (PHWR)
- Manual opening of Turbine-driven aux. feedwater pump valve (PWR)
- Connecting safety-related instrument air system for manual opening of SG PORVs and pressurizer PORVs in MCR (PWR)
- Driving mobile generator and connecting to the bus (common)
- Connecting mobile pump to supply heat sink (common)
- Check closing status of containment isolation valves or carrying out the closing of valves (common)
- Transmitting information from the inside of reactor in the radiative contamination zone (common)

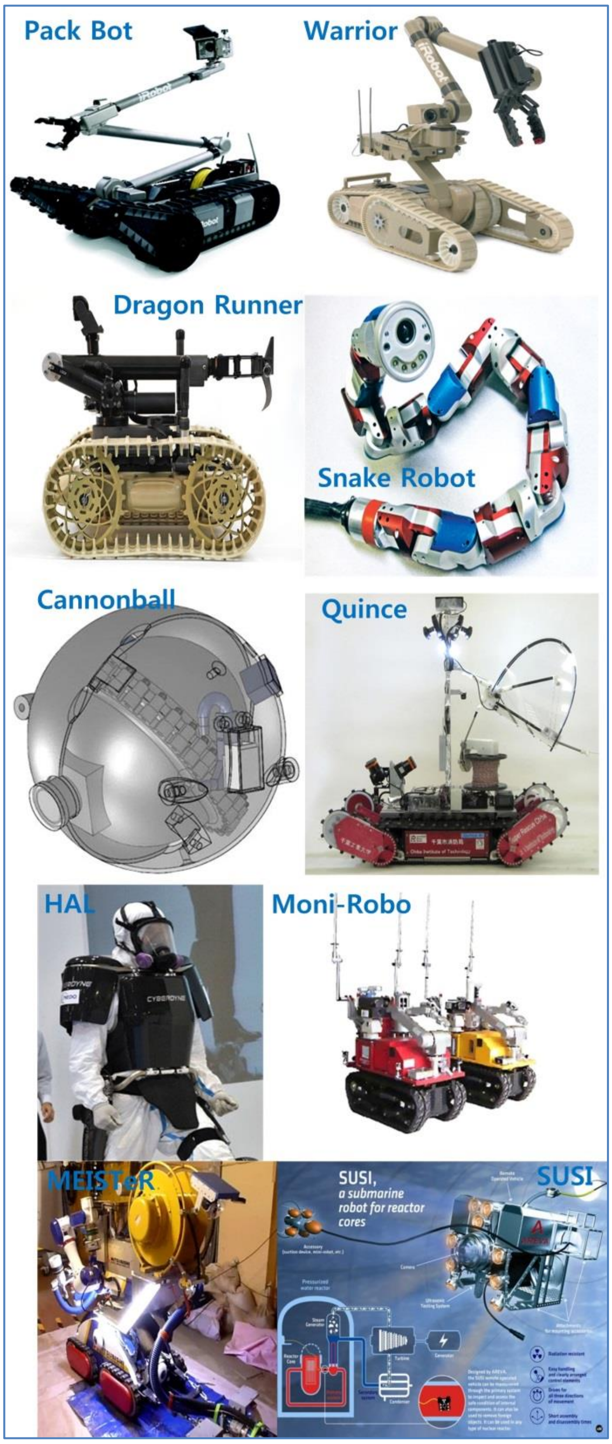

Figure 1. Robots engaged in extremely dangerous environment in the NPP for each country

- Providing information to understand plant condition after discharge of battery.

It is expected that current level of robot technology cannot reach all of the above actions perfectly. But robots can be used in the cases that require such urgent actions as opening of SG depressurization valve, closing of containment isolation valve and accessing to the high radiation area or the radiative contamination zone where it is hard for operators to access.

In particular, to detect leaking area and to deliver the information accurately with accessing to the high radiation area of the extreme conditions in containment, utilizing of robot is required.

6. Conclusions

Accurate judgment of the inside situation of the plant and quick actions in the extreme condition like earthquake accompanied by loss of all AC powers should be considered as major function in terms of prevention of accident spread. According to the reported stress test results of domestic NPPs [4, 5], the difficult things for operators to carry out in extreme conditions can be predictable, therefore the active use of robots as accident mitigation strategies will be helpful to reduce the unnecessary spending for facility improvement.

Current trend of domestic and foreign robot technology development focuses on the information search of the inside of the plant and development of preventive maintenance of NPPs. As seen actually in Fukushima Daiichi, main roles of robots place emphasis on measuring the inside radiation level accessing to the area where operator cannot access and delivering information which can support operator's decision-making and actions. Therefore, it is considered that development of robots which can take actual actions in place of operators in the extreme conditions will be an urgent issue for now. From now on, with the end of domestic NPPs lifetime, it can be considered that availability of robots as tools of decommissioning of NPPs will increase more than ever.

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