Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 27-28, 2016

A Practical Scheme to Quantify Safety Benefits of Disaster Robots

Young Choi [a*], Kyungmin Jeong [a], Inn Seock Kim [b]
[a] *Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 beongil, Yuseong-Gu, Daejeon*
[b] *ISSA Technology, Inc., 21318 Seneca Crossing Drive, Germantown, MD 20876, USA,*
[*] *Corresponding author: ychoi@kaeri.re.kr*

1. Introduction

The remote response technology has advanced to the extent that a robot system, if properly designed and deployed, might greatly help respond to the beyond-design-basis accidents at nuclear power plants especially in the harsh environment caused by extreme natural hazards. Particularly following the chaotic events at the Fukushima Daiichi Nuclear Power Station in March 2011, there is an increasing interest in developing disaster robots in the remote response technology community. The nuclear robotics team of KAERI is also endeavoring to construct disaster robots, and first of all, interested in how much safety benefits the disaster robots will bring about. The nuclear robotics team of Korea Atomic Energy Research Institute (KAERI) has long been involved in robot development for a variety of applications such as emergency refueling manipulation at a pressurized heavy water reactor and decommissioning of nuclear power plants [1]. In light of great advances these days in remote response technology and the need to upgrade the coping capabilities of the nuclear power plants against beyond-design-basis external events, a primary focus is placed on developing disaster robots [2-4] that can be deployed to the field where a disastrous or potentially disastrous event is happening. Where a decision has to be made to select a robotic mitigating measure out of several alternatives, the approach also may be applied in evaluating the safety benefit for each alternative so that the result can be used in the selection process together with other decision factors (e.g., development costs, technical feasibility).

2. Methods and Results

This section discusses a new approach based on probabilistic risk assessment (PRA) technique that can be used to quantify safety benefits associated with disaster robots, along with a case study illustration. The case study demonstrates that a significant risk reduction can be achieved by the robotic intervention.

2.1 Quantification approach Model

There are a lot of challenges that nuclear disaster robots may face; in particular, harsh environments caused by the extreme event, and unforeseen situations beyond the scope of expectation and imagination. Hence, it became necessary to identify in the first place how much safety benefits the nuclear disaster robots could bring about if properly designed and deployed to the field in accordance with the architecture for high performance that is discussed elsewhere [5]. Various types of accident mitigation actions might be performed by disaster robots in nuclear power plants in the case of extreme events causing hazardous environments. Example robotic actions include:

1) Assess the plant situation (e.g., temperature, humidity, hydrogen concentration, radiation)
2) Establish emergency flow paths by opening locked closed valves
3) Operate a portable diesel generator and circuit breakers to provide emergency power
4) Provide external coolant makeup into the reactor or the spent fuel pool
5) Conduct reconnaissance within the nuclear power plant or over the site during or following a severe accident

The approach to evaluating the safety benefits that a disaster robotic system might bring about is based on the PRA technique [6] as mentioned earlier. Although there are many different types of PRA (e.g., internal events PRA for steam generator tube rupture or loss of coolant type events; external events PRA for earthquake or external flooding type events; and Level 1, 2 or 3 PRA depending on the end state of the analysis), the risk associated with nuclear plant operation is quantified by a PRA model in terms of accident sequences that can be basically represented by:

IE * HWi * SWj * HEk * NRl

where, IE, HWi, SWj, HEk and NRl mean initiating event, hardware failures, software (or digital component) failures, human errors, and non-recovery events (e.g., failure to recover offsite power or failure to repair inoperable equipment), respectively. The subscripts imply that zero or any number of such events may be included in a specific sequence. In a special case where no such events are included at all, the initiating event directly causes the end state (e.g., core damage).

2.2 Definition of risk metric

To quantify the safety benefits of the remote response technique, a risk metric that will be used for the quantification needs to be first determined. Several different types of risk metrics are typically used in analyzing risks for nuclear power plants:

- Core damage frequency (CDF)
- Large release frequency (LRF) or large early release frequency (LERF)
- Health effects such as early fatality or late cancer fatality

These risk metrics are quantified by Level 1, Level 2, and Level 3 PRAs, respectively. Although they are typically represented in terms of annual frequencies of occurrence, there exist similar risk metrics in terms of probability, such as conditional core damage probability (CCDP), conditional large release probability (CLRP), or conditional large early release probability (CLERP). These probability-based risk metrics are used to measure the risk conditional upon the occurrence of a specific initiating event. Since the safety impact of robotic interventions will be assessed for a specific situation of station blackout, probability-based risk metrics will be used rather than frequency-based ones.

These risk metrics are quantified by Level 1, Level 2, and Level 3 PRAs, respectively. Although they are typically represented in terms of annual frequencies of occurrence, there exist similar risk metrics in terms of probability, such as conditional core damage probability (CCDP), conditional large release probability (CLRP), or conditional large early release probability (CLERP). These probability-based risk metrics are used to measure the risk conditional upon the occurrence of a specific initiating event. In this study, conditional core damage probability is used as the risk metric to quantify the robotic safety benefits. The degree of CCDP reduction by robotic interventions represents the safety impact of the accident mitigating actions performed by the robotic system.

2.3 Selection of target scenario

A critical step in the quantification approach is selection of the target scenario in which the robotic intervention will be made. A challenging scenario may be preferably selected so that substantial safety benefits can be achieved. The most challenging accident type can be found from the activities of the nuclear power community following the September 11 terrorist attacks and the recent Fukushima accident as well the state-of-the-art reactor consequence analyses (SOARCA) of the NRC. After the September 11 terrorist attacks, the NRC analyzed what might happen in the case of aircraft attack on a nuclear power plant. The largest impact in such a case was determined to be a loss of large area, especially resulting in loss of all AC and DC power at a single unit as a result of aircraft attack on the Control Room building. The Fukushima accident also involved a loss of all AC power, namely a station blackout (SBO), as a result of the strong earthquake and concomitant tsunami.

In the SOARCA consequence study the following accident scenarios were evaluated:

- Long-Term Station Blackout (LTSBO)
- Short-Term Station Blackout (STSBO)
- Interfacing Systems Loss-of-Coolant Accident (ISLOCA)

2.4 Identification of potential robotic interventions

Following the investigation of how plant personnel will respond to extreme events in accordance with the guidelines, the mitigating actions that might be performed by a robotic system in harsh environments can be identified. As there are a large variety of mitigation measures that might be conducted to cope with the evolving extreme event and the development of a disaster robot will require considerable efforts and resources, it is necessary to identify safety significant mitigation measures which will be implemented by the remote response technique. In addition, the feasibility of robotic interventions in light of the state of the art in robotics and remote systems technology should be taken into account.

2.5 Quantification of robotic safety benefits

Once potential robotic interventions are determined in connection with human failure events (HFEs), risk sensitivity analysis can be conducted for the target scenario using the computerized PRA program: 1) Case 1 without robotic intervention; and 2) Case 2 with robotic intervention. In order to reflect the robotic intervention in the PRA model, the data of the HFEs (i.e., human error probabilities) associated with the robotic intervention need to be appropriately modified. Although the robotic system may not always succeed to perform its mission, the human error probability for the HFE associated with the robotic intervention can be set to zero in order to evaluate the maximum benefit that the robotic system can bring about. The maximum safety benefit of the robotic intervention can then be obtained by subtracting the risk impact for Case 2 from the risk impact for Case 1. The larger this difference, the greater safety benefit can be achieved by the robotic intervention.

2.6 Case study

Table 1 also shows changes made to the PRA model such that: 1) the LOOP initiating event is set to TRUE to model the occurrence of a loss of offsite power; 2) the basic event for diesel generator A to fail to start and the basic event for diesel generator B to fail to start are each set to TRUE in order to model the SBO condition and also the potential common cause failures between two DGs or among three DGs; and 3) the SBO DG basic event for test or maintenance unavailability, i.e., EPS-DGN-TM-SBO, is set to FALSE so that robotic safety benefits can be quantified in connection with the SBO diesel generator. Finally, note that the basic event ACP-XHE-XM-ALT (Operator fails to start and align SBO DG) is used to model the robotic intervention such that: 1) the case of no robotic intervention is quantified with this basic event set to the new probability of 2.00x10-1, and 2) the case of a successful robotic intervention is quantified with this basic event set to zero, implying that the robotic system succeeds to start and align SBO DG.

Table I: Data modifications for robotic safety benefits evaluation

Basic Event	Description	Nominal Probability	New Probability	Remarks
AFW-XHE-XM-TDP	Operator fails to locally start TDP	4.00E-03	4.00E-02	Increased by an order of magnitude to reflect the seismic condition.
ACP-XHE-XM-ALT	Operator fails to start and align SBO DG	2.00E-02	2.00E-01	Increased by an order of magnitude to reflect the seismic condition.
EPS-XHE-XL-SBORMC	Operator fails to recover room cooling to SBO DG	1.30E-01	1.00E+00	Increased to 1.0 to reflect the seismic condition.
OEP-XHE-XL-NR02H	Operator fails to recover offsite power in 2 hours	3.18E-01	1.00E+00	Increased to 1.0 to reflect the seismic condition.
OEP-XHE-XL-NR08H	Operator fails to recover offsite power in 8 hours	6.72E-02	6.72E-01	Increased by an order of magnitude to reflect the seismic condition.
EPS-XHE-XL-NR08H	Operator fails to recover DG in 8 hours	2.96E-01	1.00E+00	Increased to 1.0 to reflect the seismic condition.
IE-LOOP	Loss of offsite power initiating event	1.30E-01	1.00E+00	Set to TRUE to model loss of offsite power.
EPS-DGN-FS-DGA	Diesel generator A fails to start	5.00E-03	1.00E+00	Set to TRUE to model SBO condition and potential CCF.
EPS-DGN-FS-DGB	Diesel generator B fails to start	5.00E-03	1.00E+00	Set to TRUE to model SBO condition and potential CCF.
EPS-DGN-TM-SBO	SBO DG unavailable due to test or maintenance	9.00E-03	0.00E+00	Set to FALSE To analyze robotic intervention in connection with the SBO DG.

The risk sensitivity analysis was performed for these two cases in SAPHIRE code. The quantification of all LOOP sequences in the PRA model for these cases yield the following conditional core damage probabilities: 1) 7.06x10-1 in the case of no robotic intervention; and 2) 3.21x10-1 in the case of successful robotic intervention. Therefore, the risk of CCDP associated with the seismic-induced SBO condition is reduced by 55% if the robotic system succeeds to start and align SBO DG within 8 hours following the seismic-induced LOOP and subsequent failure of both dedicated diesel generators. The SBO condition exists at the plant until the SBO diesel generator is successfully connected to either of the safety buses. The underlying assumptions in this regard are that all these actions will be performed within 8 hours: 1) the robot system along with the SBO diesel generator can be brought to the connection point of the SBO DG to the plant electrical distribution system in order to provide emergency AC power; 2) if there are debris on the route, the debris will be removed by a debris-removal robot; 3) the robot for mitigation action will enter one of the electrical rooms and operate circuit breakers to strip unnecessary DC bus loads; and 4) fuel continues to be provided to the SBO DG until the emergency power from this equipment is not needed any longer.

3. Conclusions

As part of the fundamental research in the robotics development program of KAERI, a new approach to quantify the safety benefits associated with the mitigation actions to be implemented by disaster robots in the case of an extreme nuclear accident has been developed. This approach is based on a PRA model, and seismic-induced station blackout condition was used as the target scenario. The case study demonstrates that a significant risk reduction (i.e., CCDP reduction of ~55%) can be achieved by the robotic intervention, provided that the robotic system performs the mitigating measure of starting and aligning SBO diesel generator within 8 hours in the station blackout condition. Where a decision has to be made to select a robotic mitigating measure out of several alternatives, the approach also may be applied in evaluating the safety benefit for each alternative so that the result can be used in the selection process along with other decision factors (e.g., development costs, technical feasibility).

Although only the action of starting and aligning the SBO diesel generator was used as a mitigating measure that might be performed by the disaster robots in this study, they could also be used for many other purposes during an extreme event. For instance, a robot could be used in providing an external injection or spray to the spent fuel pool to prevent fuel damage or reduce radiological consequences following fuel damage when no other way of injection or spray is available. Alternatively, unmanned aerial vehicles (UAVs), sometimes called as drones or unmanned aircraft systems (UASs), might be used for reconnaissance purposes in order to identify the site condition following a site-wide extreme event as caused by a strong earthquake or typhoon. The information on the site condition could be valuably used in the decision making process on how to cope with the evolving accident. Finally, it is envisioned that disaster robots, if properly developed and deployed, will significantly help to enhance coping capabilities against extreme events at nuclear power plants.

REFERENCES

[1] S.H. Kim, K.M. Jung, S.U. Lee, et al., Innovative robot technologies for nuclear power plant inspection and maintenance, ICONE22, Int. Conf. Nucl. Engr., Prague, July 7-11, 2014.

[2] B. Siciliano, O. Khatib (Ed.), Springer Handbook of Robotics, Springer-Verlag, Berlin, 2008.

[3] R.R. Murphy, Disaster Robotics, The MIT Press, Massachusetts, 2014.

[4] B.S. Dhillon, Robot Reliability, Safety, Springer-Verlag, New York, 1991.

[5] Y. Choi, K.-M. Jeong,, I.S. Kim, Strategy to enhance applicability of the KAERI's remote response technology, Trans. Am. Nucl. Soc., San Antonio, TX, June 7-11, 2015.

[6] M. Modarres, What Every Engineer Should Know About Reliability, Risk Analysis, Marcel Dekker, New York, 1993.