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Automation and Control Challenges in Fuel Debris Retrieval Operations for Fukushima Daiichi Decommissioning *

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Abstract: Fukushima Daiichi decommissioning is a long-term engineering challenge, of which advanced control techniques are essentially demanded. In the past ten years, the success in various decommissioning operations demonstrates the importance of elaborating state-of-the-art control and automation technologies. However, there are still various control engineering issues in the upcoming fuel debris retrieval operations at Fukushima Daiichi. These control issues cannot be resolved by applying existing control techniques or products, because typical control solutions do not need to consider the extreme environmental conditions and highly demanded safety requirements for operations within the post- accident environments therein. This paper and the associated discussions will introduce the automation and control challenges that need to be addressed by the control society. This aims to disseminate these control challenges to academia and industry, and therefore encourage practitioners to collaboratively develop novel solutions for the extreme engineering practice.

Keywords: Automation and control, Control engineering practice, Digital twin, Nuclear decommissioning, Remote operation, Task planning, Human-in-the-loop control

1. INTRODUCTION

In 2011, three out of six reactors, Unit 1, 2 and 3 in Fukushima Daiichi Nuclear Power Station (NPS), were in operation when the tsunami hit these reactor buildings just after Tohoku Pacific Ocean earthquake. The cooling functionality for these reactors was lost resulting in excessive overheat inside the reactors (Tokyo Electric Power Company Holdings, 2020). Consequently, nuclear fuel and some of the structures melted down into the pedestal and its surroundings. The post-accident Fukushima site has been under a long-term decommissioning process in the past decade and beyond. Due to the presence of considerable radiation hazards in various formats, every single mission for decommissioning needs to be carefully carried out following an iterative operation procedure, including surveying, planning, rehearsal, and execution steps in brief.

Motivated to enable each step in different complicated environments therein, endeavours have been made by the control society to develop various automation and control solutions. For instance, an automated management system utilised data fusion approach (combining an object detection and a classification methods) to identify and control the use of personal protection equipment (Chen, S., & Demachi, K., 2020). Automated air pollution monitoring stations were deployed by the local governments allowing for estimating transport pathways of radionuclides (Oura, Y, & et. al., 2015). Nevertheless, advanced control techniques have been developed and applied to enormous emergency response systems (see a summary from Osumi, H., 2014) and decommissioning robots (e.g., the robotic systems developed by Okada, S., & et. al., 2020).

However, the decommissioning process still faces different engineering challenges, which essentially demand elaborating the state-of-the-art automation and control techniques in the engineering practice. Specifically, fuel debris retrieval is one of the major, critical challenging missions. Success in fuel debris retrieval operations requires the realisation of a series of novel control techniques, such as digital-twin-enabled control systems, novel sensor fusion using limited instruments, automated planning of complex operations, safe human-in-the-loop control for effective intervention operations, etc. Because there is an essential need for guaranteeing operation safety in hazardous, cluttered, and confined environments, these control techniques are beyond the capability of mature automation and control solutions for common engineering environments.

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This discussion paper will introduce the fuel debris retrieval mission in Fukushima Daiichi. This allows for discussing several representee challenging control problems therein needed to be tackled. As a result, this paper and the associated discussions expect to draw the attention from the control society, and encourage collaborations between the research and industry communities to participate in developing novel solutions for the extreme engineering practice.

2. FUEL DEBRIS RETRIEVAL IN FUKUSHIMA DAIICHI

Fuel debris are the solidified composites as a mixture of the molten nuclear-fission fuel and different substances, like concrete, steel structure, etc., in Fukushima Daiichi NPS. The fuel debris has remained in the damaged three units since the accident. The Tokyo Electric Power Company Holdings (2020) is planning to start retrieving the fuel debris.

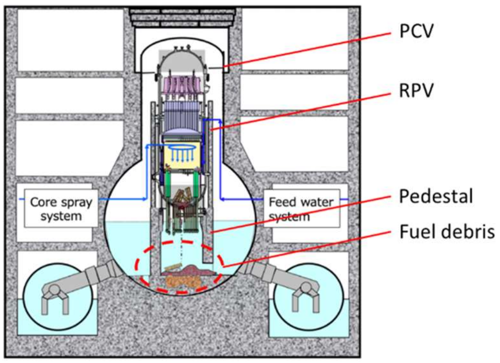

Fig. 1. Schematic illustrating the fuel debris within Unit 3.

Because the radiation level in situ (, i.e., the reactor primary containment vessel [PVC]) is too high for human workers to access (see a schematic of Unit 3 PCV in Fig. 1), it is necessary to utilise remotely operated systems for the retrieval mission. However, due to the explosion that occurred during the accident, the operation environments have become cluttered by broken, corroded, and very likely contaminated structures. The resulting significantly uncertain environments are clearly different from typical robotics applications, which are developed and intended for well-understood organised industrial conditions.

One protentional solution being developed for remote retrieval is a control system prospectively comprising but not limited to the following sub control systems:
a) a digital-twin-enabled system (see a concept design in Fig. 3) including the environmental information reflecting the inspection data (collected from the sensors) and the interactions (between the operation tools and the environment),
b) a long-reach manipulation control system allowing deployment of the inspection instruments (e.g., radiation sensors, viewing cameras, etc.) and operation tools (e.g., cutting tools, robotic grippers, and so on) over a long (approximately 20 m) distance via a limited access port (see Fig. 3), and
c) a task planning system assisting operators to decide upon and verify (via rehearsals) an optimal approach (or several optional optimum approaches) in an automated or semi-automated manner to complete inspection and intervention operation.

3. CONTROL & AUTOMATION CHALLENGES

3.1 Digital-twin of decommissioning operations

In fuel debris retrieval at the Fukushima Daiichi NPS, it is important to precisely understand the operation environment inside the PCV before staring any actual work. However, it is difficult to measure or detect detailed information for the complete environment because only limited sensors can be deployed into the unstructured PCV at a high radiation level.

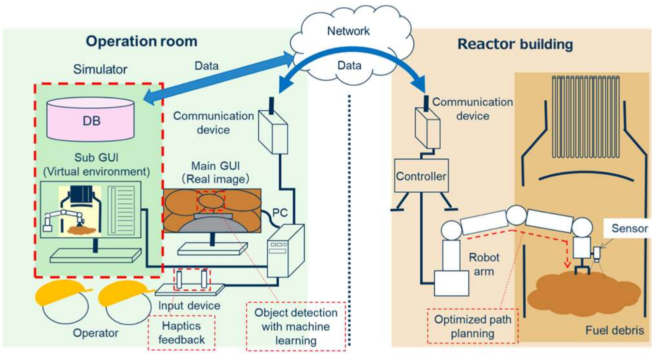

Fig. 2. Concept of the digital-twin-enabled control system.

Therefore, the visible area is planned to be surveyed at first, and then the operation space will be gradually expanded by removing obstacles and debris. As the work progresses, the visible area gradually increases, allowing subsequent operational plans to be revised with more detailed and accurate information.

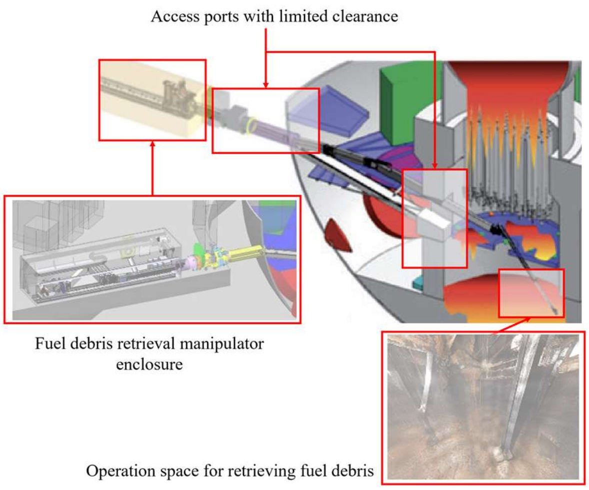

Fig. 3. Schematic of the solution using a long-reach manipulation system to retrieve fuel debris. Note that the manipulator design (Yamauchi T., 2021) may not reflect the actual mechanical design in practice. The photo only shows a part within the Unit 2 PCV (Nuclear Accident Response Office, 2020).

Practically, the installation constraints of cameras and resulting lack of viewpoints cannot provide optimal viewing locations at different angles. Thus, it is difficult for operators to remotely adjust the manipulation system at high precision. Motivated towards resolving such an issue, it is necessary to introduce a digital-twin-enabled control system, which allows for taking into account various sensing measurements and therefore generating an accurate digital representation of the operation environment for operator situational awareness. The control system will continuously update the status of the environment and the manipulation system, according to the control signals and sensor measurements. The operation status will be simultaneously updated and presented in an associated digital representation. In this way, the control system can provide the operators sufficient information and views at different angles for decision making.

It is, however, very challenging to continuously update the changes in the environment based on vision data from cameras or point-cloud measurements. This is because the structures and the obstacles are randomly broken, deformed, or corroded from their original ideal designs. Thus, it is essential to develop novel data fusion techniques, in lieu of using typical object identification and tracking techniques that cannot be directly applied to building a digital twin of the decommissioning environment. Nevertheless, the sensor fusion algorithms need to be robust against foreseeable measurement noise as a result of significant radiation.

3.2 Advanced human-in-the-loop control for safe intervention

In the fuel debris retrieval mission, the long-reach manipulation robot and its associated maintenance manipulators are planned to be controlled manually, when interventions (e.g., cutting or gripping motions) are conducted. Even during the manual operations, the system is required to monitor the operating conditions of robots and manipulators continuously and ensure the safety automatically so that the movements do not lead to dangerous situations (such as collisions with important structures). Specifically, a human-in-the-loop control strategy will be used for implementing haptic control providing both vision and haptic feedback.

It is noticeable that the visual feedback from cameras will be very limited, because there will be no overview camera set up inside the PCV. Here, one potential solution is to provide the operators enhanced viewing, simultaneously utilizing both the camera feeds and the digital-twin system.

Haptic devices will be used for conveying the feel of handling the object to be removed and the contact of the manipulator with surrounding obstacles to the operators. Also, for the fuel debris retrieval mission, the human-in-the-loop control needs to consider the space constraints, kinematics, and the singularities of hyper-redundant long-reach manipulators. Here, advanced human-in-the-loop control algorithms are needed for achieving safety guaranteed control with an absolute stability while providing sufficient transparent haptic feedback.

3.3 Multi-objective optimisation for automated task planning

The fuel debris retrieval mission is expected to be carried out at high efficiency for fast, cost-effective decommissioning. In addition, conducting any in-PCV work in an as short time as possible is also effective for assuring the electric components' performance within the robotic systems, because the robot is always exposed to high radiation doses inside the operation space.

Thus, automated optimisation for task planning is required to design an efficient execution approach taking into account the presence of radiation sources, the kinodynamic limitations of the manipulators, the space constraints, the clearance to obstacles, and so on. As aforementioned, the operation environment changes as the mission progresses, so it is important that the latest information is managed, represented and reflected in the automated control system continuously, i.e., enabling valid optimisation for task planning. Nevertheless, the multi-objective optimisation problem is likely non-convex and nonlinear laying in an infinite space of solutions.

3.4 Modeling, system identification, and control of bespoke robotic systems with significant nonlinearities

Due to the constraints of the site situation, the robotic system will be installed from a side access port far from the fuel debris at the pedestal or bottom of the PCV. This implies the robotic system may be a cantilevered long-reach mechanism. In this case, the inherently flexible long-reach manipulator will naturally behave with non-linear dynamics resulting in body deformations and multi-modal vibrations. The complicated dynamics potentially increase the risk of collisions, and the consequent instability of the end-effector tool positioning performance may result in sub-optimal performance.

As the robotic system is exclusively custom-designed for fuel debris retrieval in Fukushima Daiichi, there are few appropriate dynamics models that can be found applicable to control development. Similarly, there is no systematic approach or methodology yet for system identification and dynamic control for such a long flexible system. There is a need for developing novel control techniques suitable for long-reach systems.

4. SUMMARY

The fuel debris retrieval mission is an engineering challenge in control practice. The development of various novel automation and control systems are suggested to enable the success in this decommissioning mission. This paper discusses four representative issues and the associated technical challenges in realising these control systems.

REFERENCES

Tokyo Electric Power Company Holdings Inc. (2019). Mid-and-Long-Term Decommissioning Action Plan 2020. *Nuclear Damage Compensation and Decommissioning Facilitation Corporation.*

Chen, S., & Demachi, K. (2020). A Novel System for Automated Proper Use Identification of Personal Protective Equipment in Decommissioning Site of Fukushima Daiichi Nuclear Power Station. In *International Conference on Nuclear Engineering* (Vol. 83778, p. V002T08A048). American Society of Mechanical Engineers.

Oura, Y., Ebihara, M., Tsuruta, H., Nakajima, T., Ohara, T., Ishimoto, M., & Katsumura, Y. (2015). Determination of atmospheric radiocesium on filter tapes used at automated SPM monitoring stations for estimation of transport pathways of radionuclides from Fukushima Dai-ichi Nuclear Power Plant. *Journal of Radioanalytical and Nuclear Chemistry*, *303*, 1555-1559.

.

Osumi, H. (2014). Application of robot technologies to the disaster sites. *Report of JSME Research Committee on the Great East Japan Earthquake Disaster*, 58-74.

Okada, S., Hirano, K., Jp, P. E., Kobayashi, R., & Kometani, Y. (2020). Development and application of robotics for decommissioning of Fukushima Daiichi nuclear power plant. *Hitachi Rev*, *69*(4), 556-557.

Yamauchi T., (2021) Status of research and development conducted by the International Research Institute for Nuclear Decommissioning. J. Annals of the ICRP, 2021, 50(1_suppl): 31-36.

Nuclear Accident Response Office (Electricity and Gas Industry Department), 2020, Fukushima Daiichi nuclear power station the challenge of retrieving “fuel debris” - article No.2: what obstacles will we face?, [Accessed in Aug 2022 via https://www.enecho.meti.go.jp/en/category/special/article/detail_148.html]