Reinforced Safety-Related Condition Awareness in A Motion Planning System for Remote Manipulators in Nuclear Decommissioning

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***Abstract*—Motion planning of remote manipulators is a challenging task in nuclear decommissioning practice. Operators have to consider different safety-related factors to plan safe motions in such critical applications. Novel motion planning systems assist operators in planning collision-free motions. However, there is no effective way to reinforce the operators' awareness of multiple safety-related conditions, which are beyond the considerations of standard motion planning requirements in other application fields. This paper presents a human-machine interaction approach that monitors safety-related conditions and reinforces operators' awareness, when potential risks likely emerge. Three functions, which reinforce the awareness of manipulator-environment clearance, radiation exposure, and system limits, are implemented to realize the proposed interaction approach and reduce operators' cognitive load. A pilot study was carried out using a motion planning system enhanced with the proposed approach. The effectiveness has been qualitatively verified through the pilot study.**

***Index Terms*—motion planning, human-centred systems, nuclear decommissioning, remote operation, field robotics**

I. Introduction

Nuclear decommissioning operation is a highly specialized application area of field robotic systems [1], [2]. In such safety-critical applications, the field robots are customized with specialized tools, radiation resistance, and contamination protection. Particularly, remote manipulators are essential field robotic systems providing entry into challenging hazardous environments via access ports, which are critical for isolating the hazardous nuclear confinement from the exterior ambient [3]–[5]. On the other hand, these remote manipulators (see an example in Fig. 6) are commonly slender and long with redundant degrees of freedom (DOF) [3], [6], [7], so they are kinematically dexterous enough to navigate within cluttered decommissioning environments (as shown in Fig.1 and 2).

Commonly, these remote manipulators are teleoperated (e.g., [10], [11]) or remotely commanded to execute pre-planned motions (e.g., [12], [13]), to ensure operation safety in practice. This allows for rapid human interventions to handle unexpected situations that require immediate response, in contrast to typical robotic applications. One major reason is that decommissioning operations are highly non-repeatable. As a simplified example, a manipulator may need to cut and handle various obstacles (with a variety of shapes, weights, and hardness at different locations) to clean out an area [6]. Also, decommissioning environments are typically uncertain with unknowns, e.g., including unknown objects covered by piles of disposals [6], [8]. The presence of radiation degrades the performance of electronics, resulting in measurement noises or even sensor failure. This yields that only a few radiation-tolerant sensors can be deployed to measure environmental

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data (which may comprise noises caused by radiation) over their limited design life [14]. Therefore, in engineering practice, remote manipulation needs to be carefully planned taking into account unknowns, uncertainties, exceptions, and potential risks.

Altogether, the planning of remote manipulation manoeuvers while considering multiple safety represents a significant operation challenge. Motion planning has advanced for industrial and mobile robots [18], [19], but it is non-trivial to apply such state-of-the-art to nuclear decommissioning practice. Firstly, the limit of sensing measurements with noises makes the environmental data incomplete and uncertain, whilst standard motion planning algorithms are not necessarily developed on such assumption nor sufficiently proven accountable in safety-critical operations [18], [19]. Secondly, due to the essential demand for safety, it is necessary to plan remote manipulation motions taking into account various factors, such as radiation exposure, positioning uncertainties, obstacle avoidance, clearance of narrow ports, and so on. Differently, such safety-related considerations are not valid in standard motion planning problems.

Fig. 1. Photo of the bottom part of a primary contaminated vessel (PCV) at Fukushima Daiichi. Field robotic systems will be remotely operated to handle hazardous materials within this complicated environment safely [9].

Although the existing motion planning systems [12], [13] can suggest motions based on given collision meshes, it is still a heavily human-centred process to verify and adjust the motions of remote manipulators to handle uncertainties and consequently induced risks. To assist the planning process, the operators need to be aware of multiple safety-related conditions associated with individual motion plans. Practically, the minimum understanding of geometric constraints and discrepancy is gained by observing 2D visual feedback from limited camera views [2], [6]. Some novel field robotic systems could provide enhanced awareness of safety conditions from additional sensors (e.g., [15] providing radiation dose rate and time-of-flight distance measurements).

However, it means that the consideration of various safety-related conditions is still primarily taken care of by the operator's decision-making, according to excessive data from multiple sources in different formats. The operators therefore are commonly under high cognitive load resulting in distraction, stress and fatigue [20], [21]. Thus, new data representation methods are introduced to motion planning systems for safety-critical applications to reduce the cognitive load. For example, [13] introduced a digital twin that represents a virtual twin of the operation environment and the remote manipulators. The use of digital twins reduced operators' cognitive load by providing virtual views and depth perception in addition to 2D camera views. Similarly, in [21], the operation environment was reconstructed in 3D using available sensor measurements, and virtual representations of remote manipulation systems were integrated into the virtual environment. This helped operators associate the positions and movements of the remote systems w.r.t. the environment. Still, these state-of-the-art motion planning systems [12], [13], [21] rely on human operators to reason and be aware of safety-related conditions by associating the manipulators' motion plans with a huge amount of data in various formats cognitively.

Motivated to reduce the cognitive load in operation practice, this paper introduces a new human-machine interacting approach that reinforces the operators' awareness of safety-related conditions by monitoring key safety-related evaluations online. Therefore, the operators are free from the significant cognitive load for reasoning the potential occurrence of risks while planning remote manipulators' motions. Particularly, the proposed approach is to compute and evaluate safety-related operation conditions, using the multi-source data (like 3D meshes, design models, environment condition measurements, etc.) typically existing in a modern motion planning system [12], [13], [21]. The system highlights the areas where risks likely emerge and provides the associated numerical evaluation, only if any of the safety-related conditions exceeds the thresholds implying different risk levels.

This paper primarily presents an approach, which allows for enhancing awareness of safety-related conditions and therefore reducing cognitive load, assisting operators in planning motions of remote manipulators in nuclear decommissioning practice. Also, computational cost-effective methods are developed to compute the safety-related measures, so the operators can be aware of these conditions in real time. Significantly, the approach can be easily introduced into state-of-the-art motion planning systems that are well-tested and applicable in engineering practice. This yields significant benefits to the current critical decommissioning tasks, particularly at but not limited to Fukushima Daiichi [3] and Sellafield [4]. Specifically, Section II describes several key safety conditions that are identified as essential for decommissioning nuclear sites [3], [4], [22]. In Section III, a motion planning system for simulating decommissioning trials is introduced as a baseline system. Based on the baseline, it presents the methods to monitor the safety-related conditions online. Experimental operation trials are carried out as a pilot study showing the benefits of reinforcing operators' safety-related condition awareness in Section IV. The real-time performance of the implemented condition awareness function is reported.

II. Condition Awareness for Manipulation Systems in Nuclear Decommissioning

There are three important kinds of common considerations affecting motion plans, when a remote manipulation task is planned for nuclear decommissioning.

The first kind of consideration is the high complexity of the decommissioning environments. For example, in preparation for size-reduction of pipework within a legacy site, it is necessary to investigate the presence of radiation sources, hazardous chemicals remaining, harmful thermal zones, and so on [4]. Therefore, a remote manipulator may need to be navigated through congestion to deploy inspection instruments focusing on particularly interested zones for data collection (see an example of congested environments in Fig. 2). In particular operations, the motions shall be planned wisely to avoid highly irradiating zones to maximize the operational life of the remote manipulators. On the other hand, it is critical to collect sufficient knowledge of space constraints, including port access clearance, obstacle presence, space limitations, etc. Such information is essential to plan collision-free motions, so as to ensure operation safety. It is very difficult and non-trivial for operators to take into account all these environmental conditions collectively in motion planning practice.

Also, the motion planning processes need to consider the kinodynamic properties and limitations of the remote manipulators. As learnt from the mock-up trials using a prototype long-reach manipulator at Fukushima Daiichi, it is important to consider the flexibility of remote manipulators [3]. The flexibility will result in deformation, vibration, and other nonlinear dynamics behaviours, which cannot be simply predicted using operation experiences. To avoid collision risks, the operators need to consider the uncertain positioning errors of the manipulator caused by the dynamics behaviours. This can be achieved, for example, by planning a motion sequence resulting in small predictable deformation and retaining a large clearance to the environment. Also, an operator needs to understand the kinodynamic limitations (such as the position, velocity, and acceleration ranges), so the planned motions are practically achievable.

Another kind of main consideration is the variation of operation environments over time as the decommissioning progresses or the time goes by. For instance, focusing on the fuel debris retrieval mission at Fukushima Daiichi, the environments inside the primary contamination vessels (PCVs) continuously change over time after the accident. There is a need for using remote manipulators to clear obstacles, when the manipulator's access to a target operation position is blocked by the obstacles. As the mission progresses, the amount of obstacles and fuel debris will be decreased. The environmental conditions, such as the radiation level, chemical distribution, and space constraints, will continuously vary over the years. This means that the operators may have to adjust or re-plan the manipulator's motions often, according to the environmental changes.

Here, three important safety-related measures are prioritized after a system engineering study, including

- **clearance distance** between the manipulator and its surroundings (see Section III-B),
- **radiation exposure** of particular components (see Section III-C), and

Fig. 2. Photo of a post-operational site including tanks with pipework to be dismantled at Sellafield [23].

- **system limits** (e.g., actuation range, velocity constraints, and singularity occurence) of the remote maipulator given planned motions (see Section III-D).

Specifically, the manipulator-surrounding clearance distance gives the spatial tolerance to the positioning inaccuracy of the manipulator. The reduction of clearance increases the collision risks. Exposure to radiation affects the life of onboard electronics. The code of practice is to make the irradiated dosage reasonably low enough to avoid hardware failure. It is helpful to inform operators whether a motion plan will command the manipulator towards its limit of actuation ranges or velocities. Also, singularity is a well-known issue in the field of robotics. It is beneficial to avoid singularities in motion plans, so the manipulator can always retain sufficient controllability in need for getting rescued from abnormal events.

Accordingly, three safety-related condition awareness functions are developed to reduce operators' cognitive load while using a motion planning system, as detailed in Section III.

III. Motion Planning System with Enhanced Safety-Related Condition Awareness

A. Baseline Motion Planning System

The baseline motion planning system is developed using *MoveIt2* in the ROS2 environment. *Kinematic and Dynamic Solvers Library (KDL) plugin* and *Open Motion Planning Library (OMPL)* are used as the inverse kinematics solver and the motion planner, respectively. The ROS2 environment is adopted to ensure that the safety-relation condition awareness functions can be easily implemented, integrated, and tested. Note that these software modules have been selected to build a minimum viable system allowing for verifying the benefits of the proposed operator-assistance functions.

This system is built to plan the motions of an articulated remote manipulator [24] that was built for heavy-duty operations in safety-critical environments with radiation hazards. Here, the planning system only models the primary structure of the remote manipulator, and this primary structure consists of 7 DOF in an over 10 m length (also presented in Fig. 6 including a photo). The remote manipulator is at a starting position outside of a tightly confined environment, which is the vacuum vessel of a fusion tokamak device [25]. Operators are asked to plan the motions of this remote manipulator to

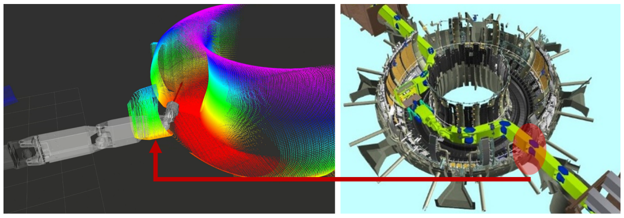

Fig. 3. The baseline motion planning system is developed for planning the motions of an articulated manipulator within the vacuum vessel of a fusion tokamak device. The highlighted area in red colour represents an access port of the vessel.

enter via a constrained port and move within the vessel. Figure 3 shows the manipulator is moving into the vessel following a collision-free motion plan generated by the baseline system.

Remark 1: The following assumptions are made without loss of generality. The remote manipulator is modelled in URDF formats assuming the geometric data is known from its design documents. The geometric data of the vessel is assumed pre-known as a result of inspection. A radiation dose map can be estimated or measured [25]. The planning system is configured as a mock-up scene of decommissioning the vessel.

B. Minimum Clearance Awareness Function

Theoretically, the minimum clearance awareness function keeps calculating the minimum inter-distance between any location at the surface of the remote manipulator body and any location at the surfaces of the operation space. This minimum distance is compared with safe distance thresholds. Once a particular threshold is exceeded in a motion plan, a visual highlight mark appears to warn operators of the locations where safe distance limits are violated.

Step 1. In preparation, it assumes that D_m is a set of point clouds covering the remote manipulator body. D_s is a set of point clouds covering the surfaces of the operation space, consisting of the constrained vessel and any obstacles therein. By splitting the surfaces of the operation space into voxel grids as sub-surfaces. D_s can be converted into a K-dimensional binary space.

Step 2. At any time t, it is possible to take a point $P_{i,m}(t)$ in D_m, where $\cup P_{i,m}(t) = D_m(t)$ and $D_m(t)$ represents the positions of all points D_m at time t, where $i = 1, 2, 3, ..., N$. Here, t can be any time point that the modelled remote manipulator is moving within the operation space. This allows for applying a K-dimensional tree search algorithm (by representing D_s as a K-dimensional binary space) to effectively find a point in D_s. At time t, given any location $P_{i,m}(t)$ at the manipulator body, it finds a particular point $Q_{j,s}(i,t)$ (from D_s) at the operation space using the tree search algorithm, yielding

$$\exists Q_{j,s}(i,t) \in D_s, \min \|Q_{j,s}(i,t) - P_{i,m}(t)\| \tag{1}$$

This point $Q_{j,s}(i,t)$ has the shortest distance w.r.t. each individual $P_{i,m}(t)$ at time t.

Step 3. Then, by traversing all N pairs of $Q_{j,s}(i,t)$ and $P_{i,m}(t)$, the closest distance is found subject to

$$\exists i_{min} \in [1, N], \min \|Q_{j,s}(i_{min},t) - P_{i_{min},m}(t)\| \tag{2}$$

, i.e., the minimum distance among all pairs of $Q_{j,s}(i,t)$ and $P_{i,m}(t)$ s.t. $i = i_{min}$. At the same time, it permits to identify particular locations where the long-reach manipulator and the operation space may most likely collide with each other, by knowing $Q_{j,s}(i_{min},t)$ and $P_{i_{min},m}(t)$. As Fig. 4 shows, when the remote manipulator is moving within the vessel environment, the shortest distance is detected using the implemented function. The green lines highlight the pairs of positions, which result in the shortest inter-distance between the manipulator body and the operation space, online.

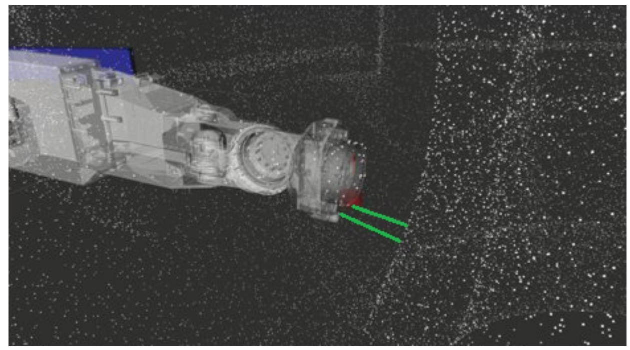

Fig. 4. Minimum clearance awareness function highlights operators where the collision risks are likely to happen in a motion plan.

Remark 2: By providing the capability of calculating the inter-distance, it is possible to configure different threshold distances, which warns the operators of different threat levels at various particular locations of the remote manipulator. For instance, if a manipulator's link has a large uncertainty in its position different from a possibly measured positional data. An operator can configure a large threshold value subject to this link, and this implies the clearance needed for this manipulator link is large in comparison to others.

C. Radiation Exposure Awareness Function

The radiation exposure calculation is implemented to support operators with understanding if any component (comprising sensitive electronics) has been exposed to a total dose exceeding given thresholds. Specifically, the space occupied by an interest component is pre-defined as a bounded region. The exposed radiation is calculated by comparing discrete point cloud intersections between the radiation dose-rate map and the occupation space region. The operators are notified if the radiation dose rate or the total exposure dosage exceeds the defined thresholds for a particular component in a motion plan.

For example, in Fig. 5, two rotational joints are considered as sensitive parts. Bounded regions in 3D space are defined as the occupation space of each joint. The boundaries are highlighted using coloured dots in Fig. 5. The dose rate map in 3D is represented as the coloured simplified map in the 2D plane.

At each time step k, the remote manipulation is moving in a radioactive operation space, i.e., the vessel here. The dose rates $r_{J,l}(k)$ ($l \in [0, 2, ..., L(k)]$), which are covered by a region

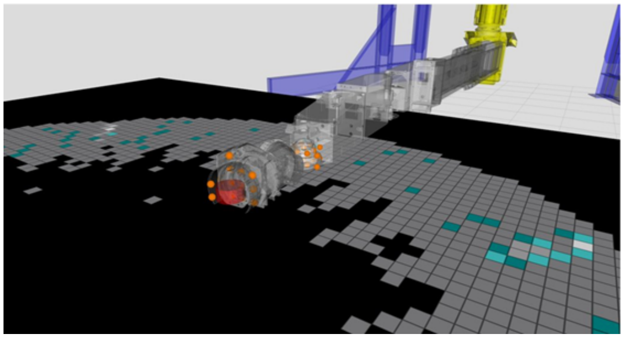

Fig. 5. Graphic representation of the remote manipulator within a radiation environment. Here, the coloured grid plane presents the radiation dose rate strength at a particular height within the vessel space.

of interests subject to a sensitive component J, are used for calculating an averaged exposed dose rate as

$$\dot{R}_J(k) = \frac{1}{L(k)} \sum_{l=1}^{L(k)} r_{J,l}(k) \quad (3)$$

, where variant $L(k)$ number of dose rate sample points are within the bounded region of component J at time step k. This allows for computing the exposed total dosage by accumulating $\dot{R}_J(k)$ over elapsed time intervals.

$$R_J(K) = \sum_{k=1}^{K} \dot{R}_J(k)\Delta t \quad (4)$$

Here, $R_J(K)$ indicates the dose exposure at joint J at the K-th time step. Δt is the time period between each discrete time of the motion planning system. The total dose is the summary of the dose over K steps of time the robot motions.

Remark 3: Note that the pre-defined radiation map [25] is a fixed map in the developed system. However, the accumulated dose at each joint is affected by many factors, such as shielding, the radiation absorbing rates of the materials, etc. Also, the radiation dose rate changes as a remote manipulator moves, due to the interferences to radiation caused by the manipulator itself. The complex radiation accumulation effect needs to be simulated by specialized programs. The presented implementation is to demonstrate that the motion planning module can take irradiated dose into consideration, when dose rates can be computed or measured online.

D. System Limits Awareness Function

The hardware limits of a remote manipulator are known by design. The system can easily monitor, verify, and highlight whether a joint is driven approaching its positioning or velocity limitations. Also, experienced operators can observe and associate planned motion sequences without being cognitively loaded very much. Importantly, it is non-trivial for operators to realize and evaluate whether a remote manipulator is at or close to its singularities. Thus, the focus here is to monitor and reinforce operators with the awareness of singularity occurrence in motions.

The singularity awareness function is implemented by calculating the remote manipulator's singularity values at any posture online. When the singular vector is not at a full rank or any element in the singular vector is smaller than a threshold, the operator will be visually notified due to the potential occurrence of singularity.

Step 1. Let $\boldsymbol{q}$ represent a set of joint values of the robot, and the dimension of $\boldsymbol{q}$ is not necessarily defined. This implies the robot is in a particular posture, which is on a planned sequence of motions. It is straightforward to compute forward kinematic chain $\boldsymbol{F}(\boldsymbol{q})$ from the manipulator's origin frame to the end-effector frame, and then the Jacobian matrix $\boldsymbol{J}(\boldsymbol{q})$ accordingly.

Step 2. Given $\boldsymbol{J}(\boldsymbol{q})$, the two-sided Jacobi method is applied to decomposite the singular values $\boldsymbol{S}(\boldsymbol{q})$.

Step 3. The singular values in $\boldsymbol{S}(\boldsymbol{q})$ are then compared to a predefined threshold, which is typically set close to zero. If any singular value falls below this threshold, it indicates proximity to a singularity event. Certainly, a rank-deficient Jacobian may have one or more singular values close to zero, signifying potential singular configurations.

In case that the singular values breach the defined threshold, a warning message is triggered, alerting the operator or system to the presence of a potential singularity. This warning allows for timely intervention and corrective actions, preventing possible undesirable robot behaviours or instabilities.

IV. Simulations of Operation Trials

Operation trials have been designed to evaluate the effectiveness and performance of the proposed approach. In particular, a group of 5 operators were invited to complete a given motion planning task (see Fig. 6). Here, the remote manipulator and the vessel space were set in the baseline system as detailed in Section III-A. The task was to plan a sequence of motions to direct the end-effector from a starting position (outside of the vessel), passing the Goal 1 position, to the Goal 2 position. As the access port had limited clearance allowing the manipulator to go through, it was difficult to manually adjust the joint values to complete the task avoiding collisions.

Here, a comparative study was carried out by asking the operators to use first the baseline system and then the system enhanced with the safety-related condition awareness functions. The operators were with different levels of experience in practical operations. One had decades of operation experience as a responsible engineer. One had just started with simulated training. The others were in the process of finishing a training program and getting prepared as operators under supervision.

As a result, the operators have confirmed the benefits by reinforcing information about safety-related conditions according to qualitative survey results. The reinforced awareness of potential risks could provide intuitive guidance for the operators to adjust motion plans, reducing the effort needed to identify problematic motions. Specifically, the minimum clearance awareness function was found very useful and simplified the motion planning task. Note that the radiation strength was low in this test environment, the benefits of radiation exposure awareness function were not well identified.

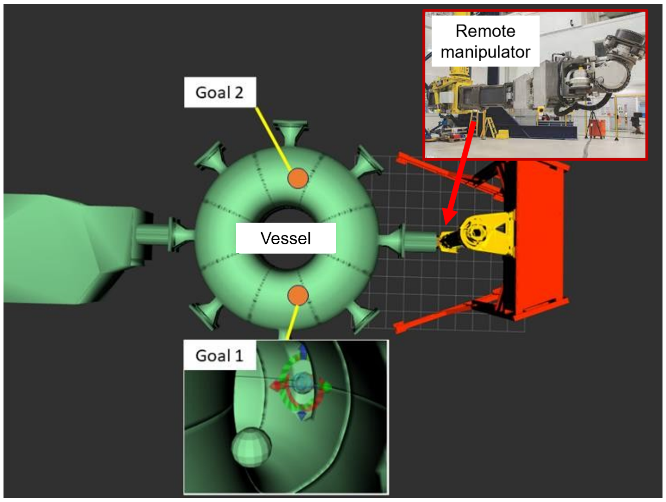

Fig. 6. Motion planning task designed to evaluate the developed functions for reinforcing operators' awareness of safety-related conditions.

This pilot study also investigated the real-time performance of the developed functions. Here, the motion planning system was implemented and tested using a standard Ubuntu 22.04 operation system with the following specifications, including an Intel Core i9-9980Xe CPU (with 18 cores running 36 threads at a 3 GHz base clock and 4.5 GHz turbo boost clock), quad-channel 64 GB DDR4 RAM (2666MHz) memory, and 1 TB NVMe SSD (Samsung 970 EVO Plus) harddrive. With the particular hardware, the safety-related condition awareness functions achieved a real-time performance as shown in Table I. Note that this performance varies with the computational power and amount of the environmental data. Using the hardware, the update rates of these functions are the minimum achievable performance on a non-real-time operation system.

TABLE I
REAL-TIME PERFORMANCE OF THE DEVELOPED SAFETY-RELATED CONDITION AWARENESS FUNCTIONS

Function	Update rate
Minimum clearance awareness	10 Hz
Radiation exposure awareness	10 Hz
System limits awareness	250 Hz

V. SUMMARY AND FUTURE WORK

This paper presents an approach, which provides operators with reinforced awareness of safety-related conditions, to reduce cognitive load in motion planning tasks for nuclear decommissioning applications. The effectiveness was verified by a pilot study that let operators at different levels of expertise complete a motion planning task. Future work will continue to develop effective human-machine interaction approaches to support with planning motions of remote manipulators. Quantitative assessments will be undertaken to evaluate the benefits for engineering practice, using the Situation Awareness Rating Technique (SART) or the NASA Task Load Index (TLX) questionnaires for example. The real-time performance needs to be verified systematically.

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