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**Irradiation Assessment of a Lightweight Industrial Robot –
Towards Faster, Safer and Sooner Waste Decommissioning – 20317**

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ABSTRACT

Robotic systems have been successfully applied in the nuclear industry for several decades as a safe approach to minimize the exposure dose of human operators. As nuclear waste management and decommissioning gathers pace, there is an emerging interest integrating modern off-the-shelf industrial robots in nuclear robotic systems which make use of complex electronics and software to improve functionality over traditional machines. The use of the industrial robots will significantly increase the pace of development of automated waste management systems at a reduced cost, and although these off-the-shelf robots are proven robust in typical industrial environments, performance in radioactive environments is less clear. This paper investigates the performance degradation of a lightweight industrial robot (KUKA iiwa 7 LBR 800) in a controlled radiation field, aiming to simulate conditions in highly radioactive nuclear waste handling facilities. The degradation of the industrial robot's performance is identified while measuring the air kerma dose-tolerance of sensitive components, via a systematic experimental methodology. The experience from this experiment has demonstrated the significant capabilities of industrial robots, which tolerated a large gamma dose of 164 Gy before a system failure. Future tests are planned, aiming to enable faster, safer and sooner waste management and decommissioning using complex robotic systems

INTRODUCTION

Simple robotic systems have been widely applied to construction, emergency response, decommissioning, and waste management by the nuclear industry [1]. For instance, in 1996, remote camera robots were used to inspect the waste stored in an area containing radiation and chemical hazards at the Hanford Nuclear Reservation (in Washington State, USA) [2]. In addition to the inspection of well-controlled areas, robotic systems also play critical roles in nuclear decommissioning tasks, where lethal radiation and complex unknown potential hazards exist, such as the decommissioning of Fukushima Daiichi Nuclear Power Plant [3]. These cases have shown that the use of robots in nuclear waste management brings significant potential benefits of safety by avoiding human exposure.

However, these robotic systems are typically developed for specific missions in the nuclear industry. Although the customized design of robotic systems can guarantee robust performances for the assigned missions, an adequate design needs a relatively long development period with respect to the demand applications. For instance [3], it took weeks to enhance only the robot vehicle control unit with thermal sensors and laser imaging systems before being deployed for field inspection in Fukushima Daiichi. Researchers at the UK's National Nuclear Laboratory have integrated different off-the-shelf industrial robotic components into a postprocessing system for solid nuclear waste material [4]. In this case, the use of the off-the-shelf industrial robots required only simple modifications and a short development period before they performed useful tasks.

The UK's Nuclear Decommissioning Authority (NDA) has reported many successful demonstrations, which integrated industrial robotic components, designed for inspection and repacking of nuclear waste stores [5]. Some of the prototype systems (e.g. the semi-automated gripping system using a KUKA lightweight robot in [4]) adopted industrial robots without considering the impact of radiation to the robots.

Off-the-shelf industrial products are almost never designed for the harsh conditions of radioactive environments and so the influence of radiation on electronic components needs to be understood before these systems are used in safety-critical applications.

In order to guarantee robust performances over extended lifetimes, it is critical to systematically evaluate the radiation tolerance of the off-the-shelf robotic components for practical applications [6]. Therefore, a series of radiation tests have been carried out to test various robotic components by the South West Nuclear Hub at the University of Bristol, aiming to underpin a practice of fast integration at low cost.

This paper will focus on the irradiation test of a KUKA lightweight robot arm, iiwa LBR7-800 [7]. This arm has seven degrees of freedom providing high flexibility in a confined working area. The robot arm has a maximum payload of 7 kg at a high load-to-weight ratio, which fits the inspection and manipulation tasks in gloveboxes [5]. Additionally, the lightweight robot is designed with a redundant safety control mechanism, which satisfies human-robot collaboration tasks, at high precision. Therefore, it is a competitive robotic manipulator promising automated operations, e.g. repacking of historic plutonium cans in sealed gloveboxes [8], safely and efficiently. The initial irradiation result will give a reference to the expected radiation tolerance of the robot in nuclear waste handling tasks by measuring the dose to failure and determining the failure mechanism from exposure to a high activity sealed source. This also suggests further investigation of the less radiation-tolerant components which might benefit from minor modifications.

Quantification of radiation tolerance and an understanding of the robot's capabilities in a radioactive environment will enable system engineers to plan the use of the KUKA LBR7-800 (abbreviated as LBR800 in the paper) or similar robots in the knowledge that tasks are within its radiation tolerance. Importantly, the deployment of robotic systems in lieu of human operators satisfies the as low as reasonably practicable (ALARP) criteria for reducing dose and hazards in nuclear waste decommissioning. The last part of the paper gives the experience and lessons gained, in order to provide practical suggestions for future irradiation tests of industrial robots.

EXPERIENMENT SETUP FOR KUKA LBR800

Irradiation test requirements and approach

The experimental setup was designed according to the requirements for the robot manipulator in a remote handling task. Typically, the maximum dose rates in ILW facilities are below 1 Gy/hr. In this experiment, a conservative dose rate of 10 Gy/hr was chosen as a target exposure as an extreme condition also applicable to high-level waste handling environments.

Typically for these types of tests, a robotic system would be assessed during a stationary exposure of radiation-sensitive components at a constant dose-rate (e.g. [9,10]). However, control performance of operating robotic components is strongly influenced by radiation in operations (see the particular irradiation test of robotic motors in [11]) and the commonly-adopted "stationary" test approach cannot assess the transient performance of the tested robotic components. In safety-critical nuclear decommissioning applications, it is critical to very closely simulate actual operations to guarantee robust performance in real applications.

Therefore, this paper suggests assessing the performance of a KUKA LBR800 via a "hybrid" approach, which consists of "dynamic" performance and "stationary" performance assessments. In detail, the "dynamic" assessment investigates the robot's performance degradation, when the robot follows a given pre-planned trajectory periodically simulating handling operations. Then, the robot is positioned in "stationary" mode being exposed to radiation at a constant dose-rate, until any system failure occurs.

Test facility and the radiation source

A gamma dose rate of 10 Gy/hr was required, necessitating the use of high activity sealed sources in a radiation cell at the UK Medical Research Centre (MRC). The cell contains Co-60 sources to generate pure gamma via β -decay. There are four sources remotely controlled to be inserted into four parallel tubes (see Figure 1). The combined radiation can be assumed effectively to be a point source in practice. A dose rate of 10 Gy/hr was obtained approximately 1 m away from the assumed point source location.

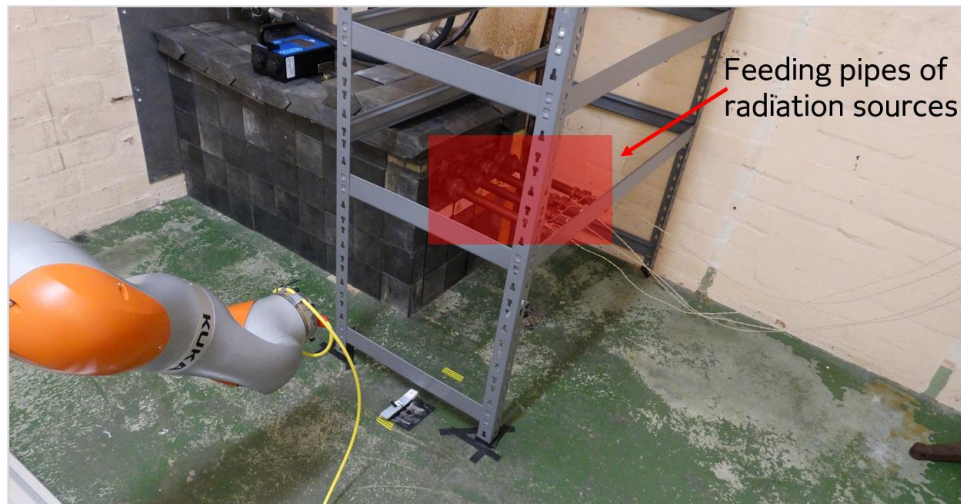


Fig. 1. A photo of the tested LBR800 in the irradiation cell. Four Co-60 sources were inserted via the highlighted insertion pipes during the experiments.

Industrial robot deployment and sensor installation

The proposed primary function of the industrial robot would be to handle nuclear waste directly or carry tools on its flange for inspection, characterization, manipulation, or size reduction. Therefore, an important performance requirement is highly accurate positioning performance in the given workspace. Typically, the position and the orientation of the flange (where tools such as grippers would be attached) must follow specific calculated trajectories. Certainly, the robot's flange would also happen to be the closest robotic component to the radioactive materials being handled, so its performance is of particular interest. The location of the LBR800's flange is marked "7" in Figure 2a.

Motivated to assess the control performance in the "dynamic" test, real-time communication was set up between a host PC and the robot controller as shown in Figure 2b. The host computer sent predefined demand signals to the robot's 7 joints (along 7 joint axes), enabling rotational motion of each joint to control the flange position and orientation in 3D. Employing the communication set-up, the robot's joint control performance can be obtained and recorded by the host computer. In practice, 100 Hz communication rate is configured in order to ensure a robust connection, using a non-real-time host-PC.

A robot's motion trajectory was required to be designed considering practical constraints:

1. The robot's flange needed to be kept a constant distance toward the assumed point source to expose it at a relatively constant dose rate.
2. The robot had to be placed at a safe distance from obstacles, avoiding any potential collisions between the robot and the environment.

A repetitive trajectory was conceived that would respect these constraints whilst allowing the robot to move continuously, thereby simulating service conditions. In detail, importantly, the robot flange was controlled to run a periodically arc motion 1 m away pointing at the assumed source location. The flange was retained

at the same height of the source. The motion speed was programmed such that traversing each arc took a period of 1 minute.

Three measurement observations were acquired during the radiation test to understand robot's behaviors:

1. Joint control performance data was collected using the data acquisition set-up in Figure 2b.
2. A diamond detector [12] measuring dose rate was placed at each of the locations marked 1-7 in Figure 2a. These were the locations of sensitive measurement and actuation electronics in each joint, so of interest for quantification of joint radiation tolerance.
3. Three cameras were placed to provide different views of the moving robot from within the radiation test cell. The video data was collected as ground truth data of robot motions.

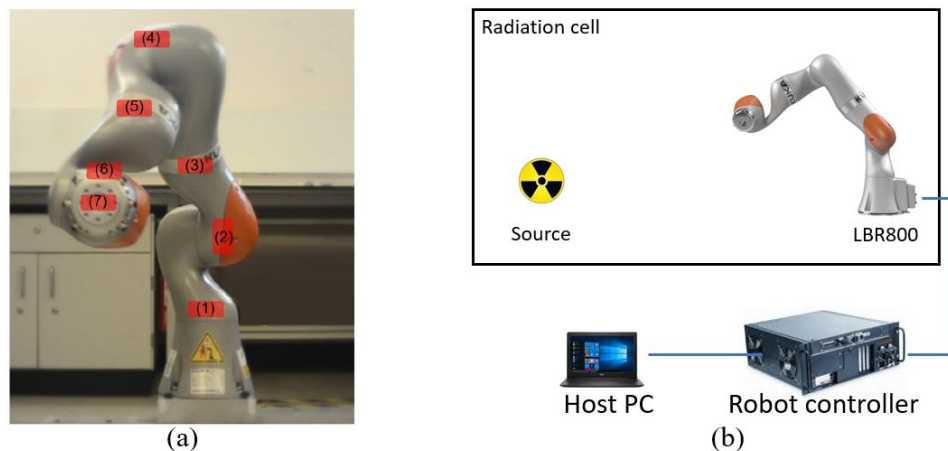


Fig. 2. The assessed LBR800 robot: (a) highlights the positions where the radiation detectors are installed in the experiment; (b) shows the control set-up that provides the target trajectory and acquires robot's data at 100 Hz sampling rate in real-time.

Experiment methodology

The hybrid performance assessment was carried out in two major stages:

Stage 1: Dynamic test to assess robot's radiation tolerance during continuous motion

This stage evaluates the LBR800's control performance of each joint axis. The robot was instructed to follow the given periodic trajectory. The control error of the robot was calculated using the real-time data by comparing the instructed joint rotations with actual values. Significant increases of the control error at any axis was considered as a degradation of the robot's dynamic performance. Obvious differences between the measured real-time robot position and the ground-truth video also denotes a performance degradation. This stage verifies the radiation tolerance of the robot controlled by its default software. Note that in practice any increased control error can be eliminated via advanced control algorithms, but nevertheless it is an useful indication of potential performance changes due to exposure.

Stage 2: Stationary radiation exposure until system failure

In stationary mode all joint axes are energized but remain still. The robot was exposed to radiation until a fatal system error occurs.

IRRADIATION ASSESSMENT RESULTS AND SUGGESTIONS FOR FUTURE TESTS

Experiment results

Following the suggested "hybrid" performance assessment approach, the dose rate was measured for

radiation-sensitive components of each joint axis at the marked locations in Figure 2a. The measurements of exposure dose rates in air are shown in TABLE I. Here, the data is processed in a conservative manner, i.e., the robot has been exposed to more radiation than the data shown in TABLE I and TABLE II.

In the “dynamic” assessment, a performance degradation of robot Axis 2 was observed after about 9.3 hours of exposure. No obvious difference was notice comparing the real-time measurements and the ground-truth. Then, in the following “stationary” test, a fatal system failure appeared after approximately 7 hours. The total exposed dose of each axis is shown in TABLE II.

TABLE I. Air kerma exposure dose rate at each joint axis in the radiation assessment

| Robot’s joint axis | Exposed dose rate during dynamic assessment (Gy/hr) | Exposed dose rate during stationary assessment (Gy/hr) |
|--------------------|---|--|
| 1 | 0.4 | 0.4 |
| 2 | 0.4 | 0.5 |
| 3 | 0.6 | 0.9 |
| 4 | 1.2 | 1.1 |
| 5 | 1.4 | 1.4 |
| 6 | 2.0 | 1.9 |
| 7 | 9.7 | 9.6 |

TABLE II. Total air kerma exposure dose of each joint axis in the irradiation test

| Robot’s Axis | Total exposed dose during dynamic assessment (Gy) | Total exposed dose during stationary assessment (Gy) | Total exposed dose before system failure (Gy) |
|--------------|---|--|---|
| 1 | 91.8 | 72.7 | 164.5 |
| 2 | 19.1 | 14.4 | 33.5 |
| 3 | 13.4 | 10.6 | 24.0 |
| 4 | 11.3 | 8.7 | 20.0 |
| 5 | 6.4 | 6.8 | 13.2 |
| 6 | 4.3 | 4.0 | 8.3 |
| 7 | 3.8 | 3.0 | 6.8 |

The LBR800 stopped functioning after a large radiation dose of 164 Gy. The point of failure was found to be Axis 7, where an optical encoder reported having a critical error. This figure provides an indication of radiation performance, but in practice due to the probabilistic nature of the interaction between photons and matter, and manufacturing variations of electronic devices, future testing may cause failure above or below 164 Gy.

Lessons and suggestions

As soon as the system failure occurred at Axis 7, the robot was locked by its safety control feature. It was impossible to continue to measure the radiation tolerance of the other joints, which reported no errors. Although the safety design stops the robot control due to hardware errors, this feature would prevent robot movement in case of emergency. In practical nuclear applications, the robot safety mechanism might be modified to allowing retrieval of the robot after failure of selected non-critical components. On the other hand, overall the safety control system is a benefit to nuclear applications.

In this work, the robot’s control performance was assessed by the control error. This is mainly due to the insufficient communication rate of the real-time set-up. The variation of control performance needs a

sampling rate of 1 kHz, which is suggested in [11] testing a fully customised motor control system. For assessing industrial robots, this is limited by the manufacturer in determining the robot functionalities. Specifically, for the LBR800 robot, the use of real-time capable machines is suggested for robot control, allowing sufficient data-richness and guaranteeing robust communication.

Additionally, the manufacturer restricted access to low-level robot control data, e.g. driving current of each motor, i.e., it would be difficult for design and test engineers to precisely identify the hardware issue after performance assessments. Unlocking such restrictions would permit the use of low-level measurements to accelerate the development speed for nuclear robotic systems.

CONCLUSIONS AND FUTURE WORK

This paper investigates the radiation tolerance of an industrial robot – KUKA iiwa 7 LBR 800. The degradation of the control performance was observed after 9.3 hours of dynamic operation in a constant radiation environment. The robot system remained functional until a failure of an optical encoder (of Axis 7) after a cumulative exposure of 164 Gy over a total 16 hours period. The encouraging radiation tolerance results demonstrate promising uses for such an industrial robot in nuclear decommissioning and waste management tasks. By introducing appropriate sensors and manipulators, these modern robots have the potential to deliver cost savings and safety improvements to the industry.

The future work continues measuring the radiation tolerance of all the joints. The research will develop radiation hardening techniques, which are easily applied to industrial robots for an improved lifetime in radiation environments.

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