Automatic, Vision-Based Tool Changing Solution for Dexterous Teleoperation Robots in a Nuclear Glovebox*

Joshua Blake[1], Guy Burroughes[2][0000−0001−8431−4637], and Kaiqiang Zhang[2],**[0000−0002−2990−2943]

[1] University of Nottingham, Nottingham, NG7 2RD, UK
[2] RACE, UK Atomic Energy Authority, Abingdon, OX14 3DB, UK

Abstract. This paper describes a novel automatic solution for tool-changing operations using dexterous teleoperated robots in a nuclear glovebox. This solution can identify and locate tools in the nuclear glovebox by visually tracking augmented reality (AR) tags online at a low computational cost. The solution is designed in a modular manner taking into account different practical constraints, so it can be easily adapted to enormous existing nuclear gloveboxes. In practice, the proposed solution is introduced to an existing robotic system including two teleoperated lightweight manipulators in a nuclear glovebox. The experimental tests have demonstrated the effectiveness of the automated tool-changing solution without any knowledge of the mock-up environment a priori.

Keywords: Nuclear glovebox · Vision-based control · Automation · Teleoperation robot.

1 Introduction

The presence of severe risks to human operators is a long-term issue when using gloveboxes to manipulate nuclear materials and wastes. The interior of a glovebox is commonly a highly cluttered environment containing radioactive materials and contaminated tools, including corroded and sharp objects threatening to human operators [6,5]. For instance, gloveboxes being decommissioned often contain exposed wires, cropped cables, pipes or needlesticks, all of which may lead to lethal incidents [15]. Thus, the industry has an increasing interest in developing robotic solutions for replacing manual operations in the nuclear gloveboxes. However, there is not yet an automated system capable of conducting complicated in-glovebox tasks, e.g., repackaging radioactive waste canisters

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** Corresponding author email `kaiqiang.zhang@ukaea.uk`

[16], demanding significant dexterity. Also, it is challenging to fit robotic manipulators inside enormous existing gloveboxes, which are originally designed for manual operations, with limited access, light and visibility (see examples in [15]). One promising solution is to introduce teleoperated robotic systems that allow for dexterous human-in-the-loop control. As a prototype, a teleoperated robotic system has been developed for nuclear-glovebox operations [20]. This robotic system integrates commercial-off-the-shelf collaborative robots with vision and haptic feedback systems, i.e., facilitating a teleoperation system in a glovebox. Thus, skillful human operators can remotely manipulate the robotic systems to complete tasks in a manner similar to traditional manual operations.

In general, an in-glovebox task needs various specific tools to complete a series of different operations, such as, radiation inspection, unfastening bolts, cutting metallic containers, cleaning surfaces, etc., inside the confined, cluttered interior space [20,12]. For example, an operator may require a powered handheld cutting tool for size reduction, a near-field scanner for radiation inspection, or a brush for cleaning surfaces, and switch between different tools in an operation. Although human operators can easily change manual tools via natural hand grasping and placing, it is non-trivial and technically challenging to manipulate teleoperated robots for grasping nuclear-glovebox tools originally designed for manual operations [20,13,18]. Motivated to achieve high operation efficiency, it is essential to develop an effective tool changing approach that allows the robots to easily locate and interface with any required tool with minimum operator inputs.

Specifically, at the Los Alamos National Lab (LANL), a completely automated line has been developed for processing nuclear material in a glovebox [10]. In detail, a 5 degree-of-freedom (DOF) robotic manipulator is installed on an automated Moore lathe, which allows for positioning of the manipulator above a stationary tool holding rack. The robot has a special flange compatible with the tools' quick-changer interfaces. Because each tool rests at a predefined location on the rack, it is possible to preprogamme the robotic system following fixed trajectories for changing tools automatically. However, this robotic solution is generally designed as an embedded subsystem of the glovebox. It is neither cost-effective nor possible to fit such an automated robotic system into common nuclear gloveboxes (genuinely designed for manual operations). Moreover, regarding a common nuclear glovebox fitted with a highly dexterous teleoperated system like [20], it is infeasible to introduce quick changers to the robot flanges. This is because the relatively high weight of quick-changer interfaces will reduce the manipulation capability of the telemanipulators (each fitted into gloveboxes via a standard 6 or 8 inch hole [21]) with limited payloads. Also, it is difficult to fit manual operation tools in various shapes with quick changer interfaces. On the other hand, clearly, the use of a tool-managing rack is an effective approach to organise various kinds of tools inside standard gloveboxes.

In the nuclear industry, it is common to add vision-based control functions into existing robotic manipulation systems, motivated to enable new functionalities, e.g., [8,14,1]. Rather than introducing an additional system (similar to

[10]) into standard gloveboxes, a potential solution for automatic tool-changing is to automatically grasp and place tools via different vision-based approaches. In [8], a surface construction algorithm is developed to use stereo-camera data for building the geometric data of unknown objects in 3D. The constructed 3D models can then be interrogated to find suitable grasp points. This offers an online decision-making approach for an industrial manipulator to grasp nuclear wastes in unknown shapes. However, depending on a series of user-defined criteria, this vision-based approach leads to variable grasp locations for the same grasping task, i.e., yielding a lack of automation and repeatability. Differently, in [1], depth cameras are used to measure the geometric point clouds of objects in a glovebox. The geometric data is then used for classifying the type of each object according to a trained classification database. The robotic manipulator will then grasp an object at specific positions that are predefined for every type of objects. Although this approach guarantees the repeatability of grasping motions, the classification of in-glovebox tools in various shapes is a non-trivial task requiring extensive data-processing to get reliable results from large databases.

An alternative, repeatable vision-based control approach is to use augmented reality (AR) tags to guide automated robotic motions. Specifically, an AR tag is an encoded fiducial marker that can be extracted from live camera feeds at a low computational cost. Thus, a vision-based system can efficiently track the AR tags, which can be attached to landmarks in an environment or objects to be manipulated. For example, an AR tracking method is utilised to track the positional and rotational data of mobile robots accurately in [7]. In a nuclear glovebox application, the position of a hand is AR tracked using the RGB-D data from a fixed camera in [19]. This allows for optimising automated collision-free motions of a robotic manipulator sharing the same workspace with the human hand. It can be seen that AR tracking methods can be used to develop a vision-based control approach for automated grasping and positioning operations, although no similar solution has not yet been developed for operations in nuclear gloveboxes.

This paper presents a novel vision-based solution for changing tools automatically at high efficiency using robotic manipulators in nuclear gloveboxes. The primary focuses are to develop the essential mechanical components and robotic system design, taking into account the constraints and considerations in the associated nuclear-industry practice. These considerations lead to the creation of a generic solution suitable for different nuclear gloveboxes. Another focus here is to describe how the functional software modules are adopted, motivated to implement a robust solution at a low-computational demand.

Specifically, a compact mobile tool management rack is designed for organising various tools inside gloveboxes. Two mechanical interfaces are designed to introduce a special kind of mating interfaces to various types of tools for nuclear glovebox operations. The modified tools therefore can be placed on and taken from the management rack using robotic manipulators at ease. Benefiting from these special mechanical designs, a novel vision-based control solution is developed integrating various functions in the robot operating system (ROS) environment. The solution processes the native RGB data from cameras providing fixed views in a glovebox. Each tool loading and unloading position is AR tagged, so they can be located and managed online by the vision-based robotic control system. This allows for automatically planning and manoeuvring of the robotic manipulators in a glovebox for loading and unloading an objective tool. The effectiveness of the proposed automatic solution has been demonstrated in practice using a mock-up nuclear glovebox. The mock-up setup consists of two teleoperated manipulators similar to [20].

2 Practical Design Considerations

In the nuclear industry, gloveboxes vary dramatically in size and shape as well as in intended applications. Motivated to develop a generic solution compatible with different gloveboxes, it is essential to design the automatic tool changing system with high flexibility. The system design needs to take into account a variety of important practical considerations as follows.

The first major consideration is that gloveboxes likely contain a variety of semi-permanent objects inside that are being stored or broken down (see [12] for example). Depending on the space required for specific operations in certain gloveboxes, there may be limited options for where the tools can be placed and organised inside the gloveboxes. Here, a tool management rack is adopted to host tools efficiently, inspired by the concept of using a tool rack in [10]. Motivated to guarantee high flexibility of the solution, the management rack needs to be mobile and able to be positioned freely inside different gloveboxes. Therefore, the rack can be moved to any position resulting in maximum operation efficiency.

Secondly, the size and shape of the mobile tool rack need to be designed carefully, because there are very limited approaches for transferring equipment into and out of the glovebox's interior workspace. The common approach for posting tools into or from a glovebox is through one or several antechamber ports located on the glovebox sides. An antechamber is typically designed with a small, well-sealed door in order to isolate the hazardous interior from the external ambient environment. This means that the tools and the associated management rack need to be small enough for being transferred through the standard antechambers.

Considering the size limitations of the glove ports or the antechambers, it is also challenging to accommodate robotic manipulators that can fit inside gloveboxes. This constrains the choices of robotic manipulators that can be introduced via standard glovebox ports (originally designed for manual operations). Despite the size limitation, the robotic manipulators need to be dexterous enough to undertake the vast series of operations, i.e., enabling remote operations inside gloveboxes. As a result, the dimensions and kinematic constraints of the suitable robotic manipulators naturally imply the limitation of the manipulators' payload. Motivated to retain high dexterity, it is necessary to maximise the operational payload of the robotic manipulators and avoid attaching accessories. Thus, heavy end-effectors and common industrial tool-changing interfaces (such as electromagnetic [2] or pneumatic [11] tool changers) are not suggested, because they would take up a significant proportion of the available payload. Because a teleoperated robotic arm with a two-finger gripper has been a well-proven design successful in teleoperation missions for thousands of hours [4], a lightweight two-finger gripper is adopted as the end-effector. As electromagnetic or pneumatic tool-changers are not recommended, it is infeasible to develop an automated solution relying on quick-changer interfaces similar to [10].

In addition, the teleoperated manipulators need to be capable of interfacing with (for instance grasping) the existing manual tools that are specifically designed for processing nuclear materials. As a result, manual operations can be easily replaced by teleoperations using the existing tools in a cost-effective manner, rather than investing to develop new bespoke tools purely for teleoperations. Helpfully, numerous tools have been designed for teleoperations over decades [9,3], motivated to maintain nuclear-fusion reactors. These tools are designed with special kinematic mating interfaces that are naturally radiation hardened and capable of ensuring consistently robust tool-grasping. Because such mating interfaces are implemented via mechanical designs, it is easy to introduce the same interfaces to the existing in-glovebox manual tools with minimal modifications. This beneficial design concept is adopted here by using a gripper finger design (see Figure 4) and a gripping block design (see Figure 2a).

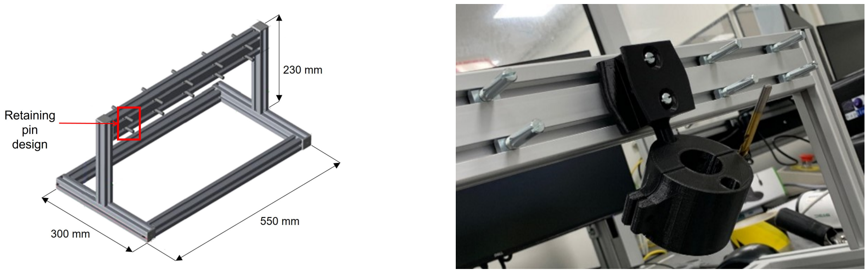
Overall, the automatic tool changing solution needs a mobile tool management rack of which the size is customisable according to the constrained access via glovebox ports, and robotic manipulators that employ two-finger grippers with special mechanical interfaces. The associated interfaces can be easily introduced to existing manual tools for in-glovebox operations. Thus, the robotic system can grip either the manual tools (designed for standard nuclear glovebox operations) or the remote handling tools (developed for nuclear-fusion operations) for teleoperations. Alongside this should be an automatic control system which allows for the changing of the gripped tool using the robotic manipulators. This tool should be selected from a range of tools hosted on a tool management rack in a robust and repeatable manner.

3 Tool Management Rack and Interfaces

This section presents the design of the mechanical components, as aforementioned, which are designed to facilitate the automatic tool changing solution. Specifically, these mechanical components include a) a tool management rack for storing teleoperation tools in a glovebox, b) remote-handling grip blocks with special kinematic mating interfaces, and c) two kinds of tool interfaces allowing for adding grip blocks onto different manual tools. Note that all the mechanical components are designed according to a specific glovebox as a representative demonstration similar to [20].

Tool management rack

The tool management rack (see Figure 1a) is designed primarily following two design considerations. Firstly, different teleoperation tools need to be stored on



(a) (b)

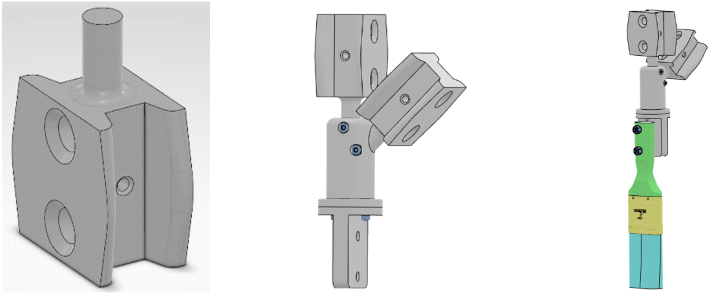
Fig. 1: Tool rack design (a) and a photo showing a remote-handling grip hosted at a tool rack (b).

the rack that could be placed anywhere inside the glovebox. Secondly, the rack could also be easily fed into and out of the glovebox through pre-existing transfer ports, specifically, an antechamber in this paper. Here, aluminium extrusions are adopted to construct a strong but lightweight supporting structure. As a result, the structure is light enough for robotic manipulators with a limited payload to lift and manoeuvre the rack. The use of extrusions also ensures the possibility of customising the size of the rack, depending on the dimensional limitations of the glovebox and its access antechamber.

The other design element is the retaining pins as highlighted in Figure 1a. There are pairs of retaining pins in parallel designed on the horizontal primary beam of the rack. Each tool or grip block has one or several pairs of holes. By mating the pair of pins and holes, it realises a stable way of hosting a tool on the tool rack as Figure 1b shows. This figure demonstrates how a remote-handling grip block (see Figure 2a and the design details below) is stably attached to a management rack. Once a tool is gripped by a robotic manipulator successfully, the manipulator can take/put the tool from/onto a management rack via a linear motion parallel to the pins. Such a linear motion can easily be carried out in either a teleoperated or automated way.

Remote-handling grip block

Here, a remote-handling grip block is designed as an interface between the teleoperated robot with different tools. Motivated to maximise the compatibility with nuclear fusion tools, the blocks are designed following the grip design principles that have been well established through years of teleoperation in [9]. Note that the grip blocks here require slight modifications to be compatible with the tool management rack. An essential modification is the addition of a pair of through holes with lead-in angles. The chamfered holes can passively guide a grip block being inserted into a pair of retaining pins, following the design principles in [9,3]. This design therefore effectively reduces the required accuracy in the robotic manipulation. As a result, the design of remote-handling grip blocks is given in Figure 2a. Figure 1b shows a grip block is firmly put onto a tool management rack. Here, the bottom of the grip block is attached with



(a) (b) (c)

Fig. 2: Gripper block design (a), tool interface design with a bolting feature (a) and an example of using the tool interface to make a manual brush compatible with remote handling operations (b).

a tool interface, which makes a manual tool compatible with remote handling operations. The design of two kinds of tool interfaces is described as follows.

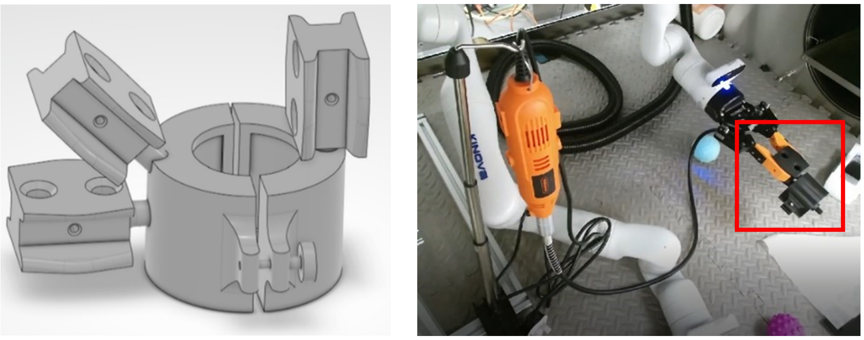
Tool interfaces

Two types of tool interfaces are designed to introduce remote-handling grip blocks to manual tools in different ways. Thus, various manual tools can be converted to be compatible with teleoperated manipulators.

One tool interface design is with a bolting feature shown in Figure 2b. One part of this interface design contains two holes where two grip blocks can be inserted and secured (see Figure 2b). The other part of this interface primarily is a flat plate with two bolting holes. Such a feature allows for bolting any manual tool with a handle firmly. For example, a manual brush (presented as the coloured model in Figure 2c) is installed to a tool interface of this type.

This interface design realises a simple, reliable method of providing manual tools with standardised grasp points for robotic manipulators. In Figure 2b, the two grip blocks can be attached separately for single-robot manipulation or as a pair for collaborative manipulation. Furthermore, the rotation of these grip blocks can be easily customised, depending on the required angle of operations or tool configurations. However, sometimes modifications are needed for installing such a tool interface to a manual tool. As an example in Figure 2c, a brush with a long handle would require the shortening of its handle and drilling of through-holes for installing such a tool interface. Although such a modification is acceptable for simple tools (e.g., manual brushes) with handles, this would not be possible for complex manual tools (such as the manual cutting tool highlighted in Figure 3b). Also, once a tool is mounted below the interface, the assembly is often significantly long. This may lead to spatial difficulties in operational dexterity and storage, considering the limited space in gloveboxes.

The other type of tool interfaces includes a clamping feature as Figure 3a shows. This tool interface design includes a hinged clamp consisting of two halves. The internal surface of each half is rubberised filling, which provides pliancy



(a) (b)

Fig. 3: Tool interface design with a clamping feature (a) and a teleoperated manipulator holding a rotary cutting tool with this type of tool interface (b).

and extra friction, ensuring secure clamping of the tools. This design allows for clamping tools in various complex shapes without the need for any physical modifications. There are three holes designed for installing remote-handling grip blocks (see Figure 3a). In practice, a specific tool can be clamped by such a tool interface with one or more grip blocks, enabling efficient tool configurations. Specifically, a manual hand cutting tool is held by a robotic manipulator as marked in Figure 3b as an example.

Such an interface design allows for fitting grip blocks with a wide range of tools, such as sanders, screwdrivers, cutters and so on, which could hardly be attached to the aforementioned bolting feature due to the presence of electronics in their handles. Similar to the tool interface with a bolting feature, there are a number of positions where remote-handling grip blocks can be installed at any rotation depending on the use case of the tool. Also, it is possible to adjust the clamping tightness and the rubber filling to change the clamping friction and damping, i.e., resulting in stable and effective use of different tools for telemanipulations. The drawback of having this clamp, however, is that it contains moving parts and joints which could be potential points of failure. Additionally, the need for components, such as hinges and spaces for installing grip blocks, results in a broad tool assembly.

On the tool management rack (see Figure 4), an AR tag is stuck onto each tool hosting position, where a remote-handling grip block installed on an operation tool is to be placed. Because a tool can be secured on the tool management rack by inserting an associated grip block into the retaining pins, this yields the position and orientation of a grip block are relatively consistent w.r.t. its hosting position as shown in Figure 1b. Therefore, by tracking the hosting position of an objective tool, the position and orientation of the hosted grip block can be calculated accordingly online. As the grasping points at each grip block are known a priori, it is straightforward to control a robotic manipulator to grasp

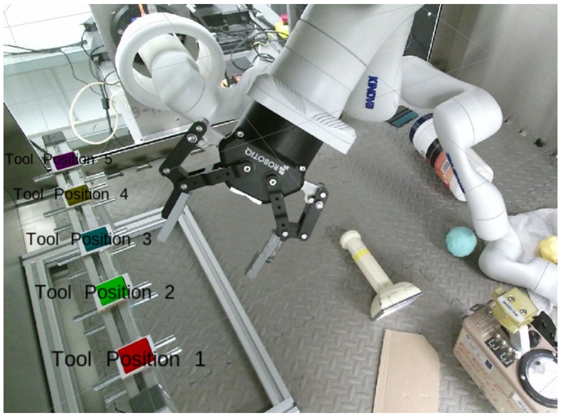


Fig. 4: Tool hosting positions are tracked online using AR tags in the experimental glovebox (overlaid by coloured markers in this figure). A tool hosting position is where a pair of retaining pins match with a remote-handling grip block. In practice, a tool with a tool interface will have one or more grip blocks.

and then move any objective tool (hosted at the tool rack) that is always tracked by a robot control system.

4 Integrated System for Automatic Tool Changing

The automatic tool changing solution is designed in a modular, highly compatible manner. Thus, the integrated system can be deployed to different systems consisting of different hardware and running in different operating system environments. The system is integrated using the Docker software platform, which allows for deploying software as packages in different operating systems. By designing each function in the integrated system as an independent container (i.e., a functional module), the integrated system can be developed and built up in a modular way. Thus, it is possible to easily adopt suitable software for efficiently use of specific hardware in practice, i.e., facilitating a highly flexible system.

Here, the system is integrated using a network-based architecture as shown in Figure 5. The network is hosted by a ROS master, which enables and manages the communications between interconnected hardware and containers. The overall system primarily consists of four containers realising different functions, including: a) a **camera container** to process vision-data from cameras and then publish the data to the ROS master, b) an **AR-tag tracking container** to process vision-data for calculating the position and orientation information of the tracked AR tags attached to different tool hosting positions (at the tool management rack), c) a **control system container** to capture the operator inputs and use the AR-tracked data to compute the demand positions for loading/unloading tools, and d) a **MoveIt container** to compute the manipulation trajectories based on the demand positions and then communicate with the manipulators for motion execution. In this ROS-network-based design, the interfaces between the containers are implemented to exchange data in fixed formats. Thus, as long as the same design is retained, each of these containers can be distributed and updated independently without the need for modifying other containers.

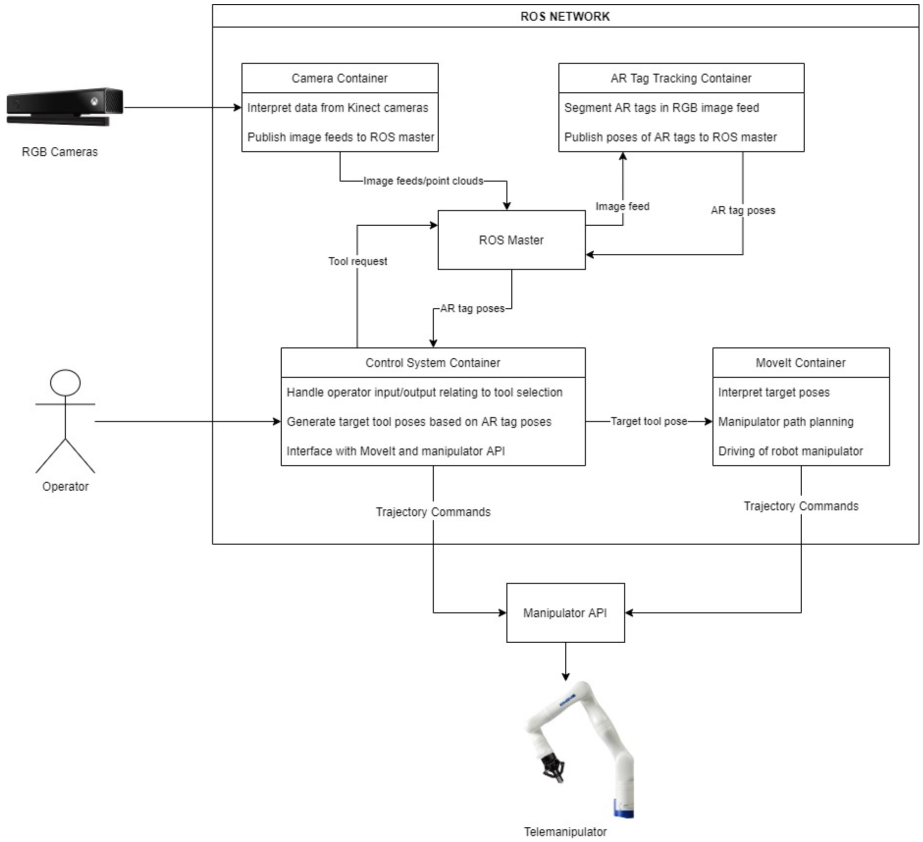


Fig. 5: Modular control system architecture.

This system integration design is applied to the experimental set-up in a glovebox tested in this paper. Specifically, to provide a clear view of the workspace, two Kinect 2 cameras are placed in two top corners of the glovebox. These cameras provide essential RGB-D data that are used for enabling teleoperation processes in the glovebox (, for example, to realise image segmentation and grasp pose synthesis in [20]). The provided RGB-D data can also be used for implementing the AR-tag tracking function for changing the teleoperation tool automatically. This avoids the need for introducing additional camera hardware dedicated to realising the AR-tag tracking function. Although it is challenging to introduce cameras into harsh glovebox environments, the use of cameras is common in the nuclear industry [8,14,1]. Thus, the installation and calibration of cameras are not a focus here and are not necessarily discussed in this paper.

The RGB-D vision data fed from the cameras is then integrated with the control system via the camera container. In practice, the camera container has been tested running with different computation hardware. Here, a JETSON Xavier System on a Module (SOM) produced by NVIDIA is recommended, guaranteeing a stable online image processing performance. This SOM consists of an 8-core ARM CPU and 32 GB of memory running a Linux distribution. Thus, the camera vision can be easily processed and transmitted as multiple image feeds and point clouds via standard Ethernet communications (see the multiple live image feeds in Figure 6 as an example). Note that the SOM is able to process the camera data and provide high fidelity point clouds at improved speed and performance, when it takes the advantage of GPU hardware acceleration.

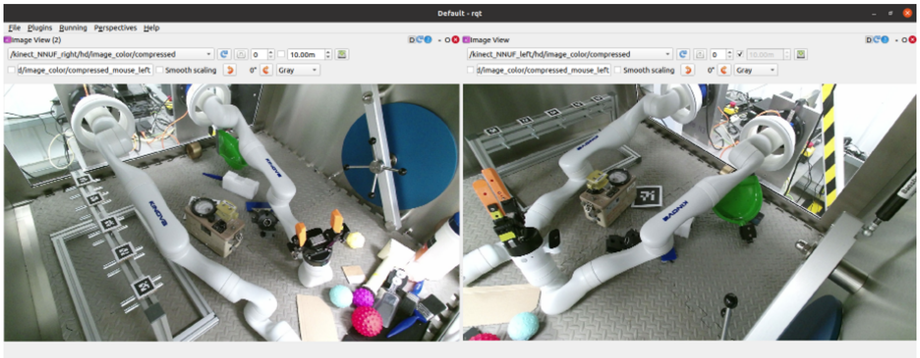


Fig. 6: Live image feeds from glovebox cameras accessed through a ROS network.

The AR-tag tracking container is mainly implemented using a ROS package called *ar-track-alvar*. Through pure image processing, the position and rotation of any number of AR tags in the camera view can be tracked and published online to a network for use by other functional modules. Specifically, the AR-tag tracking function can be achieved by using either RGB-D segmentationor RGB information only. It was assumed that using the RGB-D data could improve the reliability of tracking AR-tags rather than using the RGB vision only, as a result of introducing the additional depth information. However, using RGB-D data for tracking AR tags results in highly unstable tracking performance, because the reflections of the cluttered in-glovebox environment lead to erroneous depth data being produced. In contrast, the software achieves a robust, stable AR-tag tracking performance using the RGB vision data after optimising the border sizes of the tags and configuring the certainty tolerances in the processing software.

In experimental tests, it is found that the AR-tag tracking container can track the tags effectively online as shown in Figure 4. Here, in the user interface, coloured overlays are automatically generated to highlight the identified AR tags, motivated to assist the operator to verify the tracking performance at ease. Also, each AR tag is assigned with an ID number, which is overlaid online on the AR tags as Figure 4 shows. The software, therefore, could distinguish different tags in the environment, i.e., identifying the ID of different tool hosting locations at the management rack. It shows that these highlighted boxes match the actual positions and orientations of the tags well, and the tracking information agrees with the true positions of the AR tags in practice. Note that it is trivial to adopt a different AR-tag tracking library, as a result of the presented modular system design. This paper focuses on proposing such a robotic control system design, so the performance of different AR-tag tracking libraries is not investigated and evaluated here.

The tracked tool hosting positions are then used by the *MoveIt* container for planning the robot motions. After the operator gives a command, the control system container creates a sequence of motions which move the robot gripper for loading/unloading a tool. The *MoveIt* container uses built-in path planning algorithms to calculate the robot-motion trajectories accordingly. Motivated to ensure the repeatability of the robot motions, the important motion sequences are all pre-programmed with respect to a relative base Cartesian frame. This base frame is associated with the tool management rack, which can be identified by tracking the AR tags. Therefore, the same motion sequences can be applied, no matter how the specific position and orientation of the tool management rack are changed in operations. These important motion sequences are the linear motions that are to insert or extract grip blocks into or from the tool rack. Alternatively, the control system container can send the demand gripper positions directly to each manipulator's API. In this case, the robot paths are computed by the manipulator's built-in control system, rather than using *MoveIt*.

In practice, it is found that using the manipulator's built-in control functions can provide a robust, smooth robot-motion performance. This is because the *MoveIt* container may command the robot joints to move at a speed or acceleration exceeding the hardware limitations. Such a problem can be resolved by configuring the hardware limitations in the *MoveIt* container. The software limits need to be carefully adjusted w.r.t. specific manipulator set-ups or any changes affecting the associated dynamics limitations. In summary, the flowchart Figure 7 gives a brief overview presenting the process of how the *MoveIt* container and the manipulator API are used in conjunction.

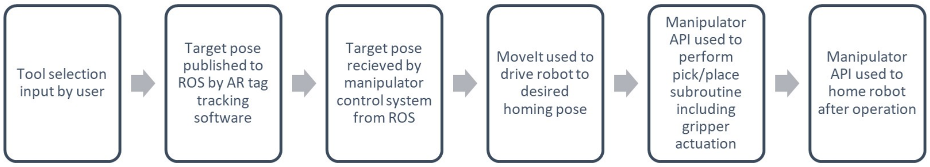


Fig. 7: Flowchart presenting how the robotic control system realises an automatic tool-changing process.

As a part of the integrated system, a user interface (UI) has been developed for testing the implemented control functions. The integrated system only requires two types of commands from an operator in operations. One type of commands is to select the objective tool to be loaded. The other type is to specify the hosting position to return a loaded tool, if there is any. This enables a simple, efficient human-robot-interaction workflow to change tools in a nuclear glovebox. It requires very little time and no operational experience to complete the tool-changing motions automatically. In contrast, it often takes a skilful operator significant attention and time to change a tool via human-in-the-loop teleoperations.

5 Results and Discussions

The performance of the proposed vision-based tool-changing solution has been tested using an experimental glovebox as a part of the RAIN project. Specifically, the experimental test rig was primarily a standard glovebox with two glove ports and one antechamber. In the glovebox, two manipulators were fed through the glove ports that normally were for operator hand access. The manipulators can be teleoperated via haptic feedback (enabled by two control robots) and vision (provided by two Kinect 2 cameras as discussed in Section 4) feedback. The tool management rack was placed inside the glovebox, and it hosted various tools with the designed tool interfaces.

In practice, the bolting interfaces were introduced to a cleaning brush, a scoop and a vacuum tube. The clamping interfaces were applied to different manual tools, such as rotary cutting devices, glass scrapers and a radiation scanner. The proposed solution has succeeded in loading and unloading these tools automatically. As the test rig included two manipulators, it was also possible to test how the automatic tool-changing solution could be used in a dual-robot collaboration mission. Specifically, one manipulator succeeded in changing its loaded tool automatically, whilst the other manipulator was teleoperated to hold the tool management rack. The effectiveness of the developed solution has been tested in the live demonstration [17] as an example.

Note that the performance of the proposed automated solution is not yet evaluated nor validated quantitatively. Specifically, for instance, the camera systems have been calibrated via a manual procedure so far. The calibration accuracy clearly affected the positioning error of the AR-tracking function. Here, an automated camera calibration procedure is recommended as a part of future work. Further in-depth analysis, which evaluates the proposed solution's robustness against the calibration errors, needs to be carried out afterwards.

Significantly, this novel tool changing solution can improve the operation efficiency of teleoperated systems designed for nuclear gloveboxes. Such an improvement is realised by automating specific operations, which are challenging and time-consuming to be carried out by human-in-the-loop teleoperations. Automatically generated manipulator movements are more effective than the movements generated by teleoperations, i.e., potentially resulting in a reduction of time, energy and joint wearing in the manipulators. Also, the automatic solution can be integrated into operational routines, which need little human intervention and change tools frequently in sequences. For example, an automatic cleaning routine may use brushes, vacuum cleaners, and radiation scanners to clean a fixed workspace surface after operations. A robotic system will need to change different tools for multiple times to complete such a routine. By introducing the proposed tool-changing solution, it is possible to automate such a cleaning routine in a completely automated manner, whereas the tool-changing operations are typically carried out by human-in-the-loop control nowadays.

Nevertheless, the integrated system is implemented in a highly flexible and modular way, using Docker containers and network-based structures. This makes it easy to introduce additional devices or features to the system. For example, when the AR-tag tracking performance using RGB-D data was tested, an additional function was used for compressing the point clouds measurements. Adding such a new function reduces the network bandwidth spent on transmitting the vision-data, without the need for changing any other containers. Also, the modular design allows for expanding this tool-changing solution to applications at large scales, e.g., facilitating automatic tool management in parallel glovebox operations employing multiple collaborating robotic arms. As a result of the highly flexible design, the integrated system can be easily modified to adapt to different legacy gloveboxes that already exist in nuclear facilities.

6 Conclusions

This paper presents the mechanical design and a robotic system design that enable changing operation tools in nuclear gloveboxes. Two types of tool interfaces are designed to make conventional manual tools compatible with remote handling operations. A mobile tool management rack is designed for storing tools considering the limitations of nuclear gloveboxes. These mechanical designs allow for robotic manipulators to automatically grasp a tool at ease and securely manoeuvre a gripped tool. AR tags are introduced to the mechanical set up, so that the developed integrated system can track the mechanical components and control robotic manipulators changing tools automatically. The effectiveness of this novel automatic tool changing solution has been demonstrated in practice. The future work will begin with investigating the influences of different camera calibration methods and AR-tracking algorithms on the overall efficiency and performance.

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