# A Teleoperated Cleaning Robot for a High Radioactive Environment

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**Abstract**: The Korea Atomic Energy Research Institute has developed a teleoperated cleaning robot for use in the radioactive zone of the isolation room of the Irradiated Material Examination Facility where direct human access to the interior is strictly limited. The teleoperated cleaning robot that was designed to completely eliminate human interaction with the hazardous radioactive contaminants has five remotely replaceable submodules - a mobile module for navigation, a cleaning module for dislodging and sucking contaminated waste, a sensing module for obstacle avoidance, a collection module for storing the acquired waste, and a cover module for protecting the collection module. This cleaning robot is capable of cleaning the contaminated floor surface of the isolation room and collecting loose dry spent nuclear fuel debris and other radioactive waste fixed or scattered on the floor surface. The developed cleaning robot is operated either by a manual control or by autonomous control in conjunction with a graphical simulator, by which the human operator can monitor and intervene the robot performing cleanup tasks in the isolation room. In this paper, we present the mechanical and environmental design considerations and development of the teleoperated cleaning robot for radioactive isolation room use. We also demonstrate its mock-up performance test results from the viewpoint of a remote cleanup operation and remote maintenance.

**Keywords:** teleoperation, cleaning robot, decontamination, radioactive environment

## 1. INTRODUCTION

DUPIC (Direct Use of spent PWR fuel In CANDU reactors) [1] nuclear fuel cycle technology is being developed at KAERI (Korea Atomic Energy Research Institute). This technology reuses spent PWR (Pressurized Water Reactor) fuel in CANDU reactors without using the wet reprocessing process. All DUPIC fuel fabrication processes are remotely conducted in the completely shielded hot-cell of the IMEF (Irradiated Material Examination Facility) at KAERI because of the nature of the high radioactivity of spent PWR fuel. These processes are very often complex and difficult to operate and require excessively careful preparation because, as the cell is active, direct human access to the in-cell is not possible.

The overriding concern in DUPIC fuel fabrication is to maintain or replace failed DUPIC fuel fabrication equipment and facilities when necessary. In the case where the fabrication equipment is damaged or broken, its electrical or mechanical parts need to be repaired or exchanged for new ones. And, when the in-cell or isolation room is contaminated with radioactive contaminants, it should be properly decontaminated in order to keep the facility sound at the certain degree of which the regulations permit. Such failed equipment maintenance and contaminated facility decontamination processes should also be conducted by robotic or remote means in order to reduce or completely eliminate worker exposure to hazardous radioactive environment [2,3].

Emphasis from the robot and remote system viewpoint is placed on decontamination or cleanup of the contaminated floor surface of the isolation room in a remote manner. The isolation room, located above the hot-cell, is used to repair or replace the failed fabrication equipment by the direct contact of human workers through the gloves installed inside, while the workers stay outside of the isolation room. In addition, new devices or fixed equipment can be transmitted to the hot-cell through the isolation room. The interior of the isolation room, therefore, needs to be maintained and cleaned to an acceptable level of radiation for a worker’s access if necessary.

However, the floor of the isolation room is inevitably contaminated with loose spent nuclear fuel debris and other radioactive waste due to the transport, disassembly, and segregation of the failed equipment that is transmitted from the hot-cell for repair or exchange. Such undesirable radioactive waste should be cleaned to prevent the contamination from spreading inside the isolation room. The floor cleanup of the isolation room should also be performed by a safer and more efficient means in a remote or autonomous manner. Therefore, a robotic system was needed to clean the contaminated floor surface of the isolation room, eliminating the workers interaction with hazardous radioactive contaminants.

The objectives of this work was to provide a teleoperated cleaning robot for both cleaning the contaminated floor surface of the isolation room and collecting the radioactive waste in a remote or autonomous manner while not endangering the human workers.

## 2. DESIGN DESCRIPTION

### 2.1 Cleanup environment

A teleoperated cleaning robot can be used for cleanup and collection operations where direct human access, even with protection, to the interior of the isolation room due to high radioactivity is not possible. Fig. 1 shows the graphical representation of the M6 hot-cell and isolation room of the IMEF for DUPIC nuclear fuel development. Fig. 2 shows the current isolation room in detail. As shown in Fig. 1, the isolation room is located above the M6 A hot-cell and has an entrance only from the left-hand side of it. As shown in Fig. 1

and Fig. 2(a), a roof door in the shape of a rectangle was installed between the ceiling of the M6 in-cell and the floor of the isolation room and is used as a channel for connecting the isolation room and the M6 in-cell. The failed M6 in-cell equipment that requires contact maintenance by a human worker can be transmitted to the isolation room via this roof door. New devices or fixed equipment can also be moved to the M6 in-cell in place through this door. The roof door is kept tightly closed during the normal operation of the M6 hot-cell and is open for equipment transmission when necessary. This roof door, however, has not been opened yet since the M6 in-cell was activated.

As shown in Fig. 2, the isolation room includes 4 shielded windows located on the wall, 8 gloves installed below each shielded window, two turning tables, one overhead crane mounted on the tracks, a roof door and one pair of master-slave manipulators. The master manipulators are located inside of the isolation room and the slave manipulators outside. The isolation room has a configuration of 6.0x2.6x2.6 (LxWxH) m. The floor of the isolation room is made of several stainless steel sheets, which are welded together to form a closed shape. The floor surface has small bumps at a maximum height of about 4 mm along the welded seam between the adjacent sheets. The upper part of the roof door is positioned about 10 mm higher than that of the floor surface when completely closed. The shielded windows provide information on the interior of the isolation room. The human worker located outside the isolation room can perform maintenance tasks via the gloves or the master-slave manipulators.

**2.2 Design development**

Based on the environmental conditions of the isolation room facility described in the previous section, the design concept and requirements of a teleoperated cleaning robot are developed. The design processes must include all the mechanical, electrical, and system integration elements required to produce a fully functional robot for remote cleanup and collection operations. Thus, the successful development, installation, and operation of the teleoperated cleaning robot involve three mutually dependent design elements – the isolation room facility, the remote or autonomous cleanup and collection operation of the cleaning robot, and the remote maintenance of the cleaning robot when necessary [4].

The design development of the teleoperated cleaning robot involves the environmental and spatial confinements of the task environment of the isolation room to be deployed, remote operation strategies, remote maintenance procedures, and the availability and limitations of the maintenance system in situ. In the design processes, a compromise should be made between these elements. The environmental and spatial constraints of the isolation room are crucial factors in determining the size, mobile means, and contamination removal means of the cleaning robot. These factors include the availability and location of the utilities for air and electricity which are necessary for operation, the geometric structure and the accessibility to the target to be cleaned, avoiding obstacles. In addition, control means greatly affects the design development of the cleaning robot. The cleaning robot should be controlled either by remote control or by autonomous control relying on the cleanup task conditions because, as the isolation room is active, the workers have no access to the work environment. Therefore, the design of the teleoperated cleaning robot should take into account the remote manipulation strategies, remote maintenance procedures and a remote maintenance system, including:

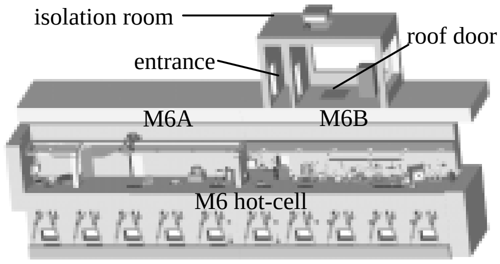
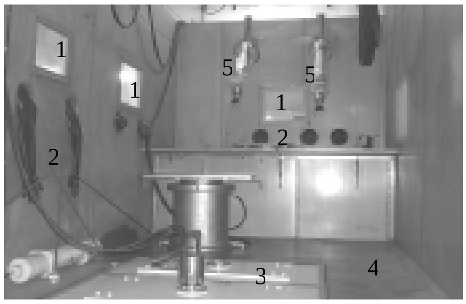
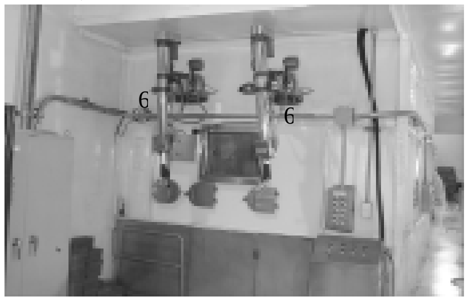



Fig. 1 The graphical representation of the M6 hot-cell and isolation room of the IMEF at KAERI.




a) The interior of the isolation room




b) The slave manipulators located outside

1: shielded windows, 2:gloves, 3:roof door, 4:floor to be cleaned, 5:master manipulator, 6:slave manipulator

Fig. 2 The isolation room of the IMEF.

- Human operator and communication – the success of the cleanup task is affected by the deftness of the human operator [5]. The operator’s experience and needs should be reflected in the overall system design process of the cleaning robot.
- Modular structure – the functional and mechanical structures of the cleaning robot should be constructed in replaceable modules or subassemblies. The failed mechanical and electrical components of the cleaning robot need to be repaired or exchanged inside the isolation room.
- Power means – the capabilities of the cleaning robot from an operating time and cleaning range viewpoint are subject to a power source and its transmission. A compromise between a battery system and a tethered power system should be made to implement the efficient control of the cleaning robot.
- Radiation Effects – the mechanical and electrical components of the cleaning robot are contaminated during operation and are affected by radiation. The radiation effects on materials to be used should be considered in the design.

## 3. A TELEOPERATED CLEANING ROBOT

**3.1 System overview**

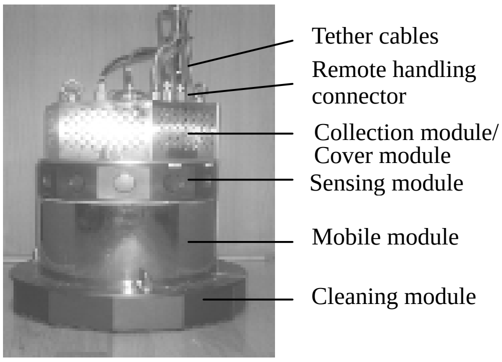
As shown in Fig. 3, the teleoperated cleaning robot was developed to clean up the contaminated floor surface of the isolation room and to collect loose spent nuclear fuel debris and other radioactive waste. The mechanism of the cleaning robot was also designed to allow for remote maintenance to be effected using master-slave manipulators and other auxiliary tools available inside the isolation room. The developed cleaning robot mainly consists of five replaceable submodules - a mobile module for navigation, a cleaning module for dislodging and sucking the contaminated waste, a sensing module for obstacle avoidance, a collection module for storing acquired waste, and a cover module for protecting the collection module. Such modular construction facilitates remote maintenance when necessary. Each module can be easily separated and assembled by remote manipulation, using a crane and master-slave manipulators. The teleoperated cleaning robot has a configuration of 465x465 (HxD) mm, a maximum speed of 10 cm/sec, an ability to collect contaminated particles of up to 0.3 μm, as well as an ability to clean up the floor surface in all directions relative to the bottom of the cleaning module of the cleaning robot.

The mobile module that employs a synchro-drive wheel assembly was designed so that the cleaning robot can navigate the floor surface of the isolation room with the welded seam. The synchro-drive wheel assembly consists of three synchro-drive wheels, which are connected together with precise timing belts. These synchro-drive wheels are driven by two dc servomotors with resolvers - one for steering and the other for driving. Such arrangement of the wheels can generate the semi-omnidirectional motions of the robot.

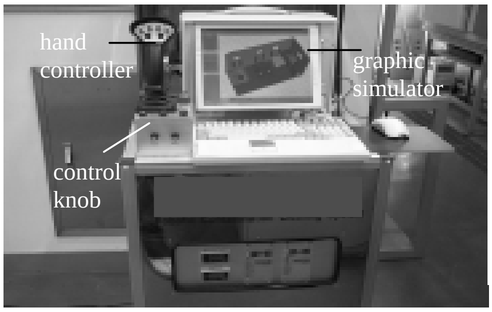
The sensing module that was designed to detect the walls of the isolation room utilizes ultrasonic sensors, which are placed around the cleaning robot in order to cover the entire area in all directions. In this work, 12 ultrasonic sensors were installed at $30^{o}$ intervals in the shape of a ring. A single drive module was used to fire 12 ultrasonic sensors. The firing sequence of the four sensor intervals was employed in order to reduce undesirable crosstalk [6] occurring by firing the multiple sensors by a single drive module.

The cleaning module was designed to dislodge contaminated waste debris fixed or placed on the floor surface and to suck up mobilized waste particles, which are captured by the collection module. This module comprises 12 compact, rotary brush tools. Each rotary brush tool consists of a small rotary brush and a rectangular shaped aluminum cover housing the brush. A thin bronze fringe was installed around the base of the aluminum cover such that it increases the cleaning ability without sacrificing the mobility of the cleaning robot. Each rotary brush tool was connected together in series, forming a circular shape. Each brush tool was, via a tube, connected to a reservoir, which is also connected to the collection module. The collection module installed on the top of the cleaning robot consists of an electrical blower and a filter box. This filter box can capture particles as small as 0.3 μm and can be removed easily for exchange. As the brush rotates, both soft and hard contaminated wastes are dislodged and the collection module then removes and stores them. The cover module installed on the uppermost top protects the collection module.

The cleaning robot can be remotely connected to an electrical power source outside the isolation room through 20 m long tether cables. Remote handling connectors that can be easily connected and disconnected by a master-slave manipulator were used to transmit all the electrical signals between the cleaning robot located inside the isolation room and a control console located outside the isolation room. These connectors were installed on the top of the cover module of the cleaning robot so that the tether cables cannot obstruct the navigation of the cleaning robot.




a) the cleaning robot to be located inside of the isolation room




b) the control console to be located outside of the isolation room

Fig. 3 The developed teleoperated cleaning robot.

As shown in Fig. 3(b), the control console provides a control location for the cleaning robot. The control console is the interface device between the operator and the cleaning robot located at a remote site. All the functions for controlling the cleaning robot are contained in it. The control console mainly includes a two-axis handcontroller for navigation, control knobs for cleanup and collection, and a graphic simulator for monitoring and path generation. The controller, circuitry, power supplies, and necessary software are also installed within the console.

### 3.2 Graphic simulator

The shielded windows installed on the wall of the isolation room provide the human operator with the inside information or situations of the isolation room. The human operator monitors the cleanup operation of the teleoperated cleaning robot relying on the visual information provided through the shielded windows. In this work, a graphic simulator was developed to provide the operator with added vision information and a more useful means for developing an improved ability to simulate and control the cleaning robot to be operated in the high radiation field of the isolation room where direct human access is limited to the strictest minimum.

The graphic simulator largely consists of a graphical model of the teleoperated cleaning robot and a graphical model of the isolation room (refer to Fig. 7). This simulator allows the operator to simulate any desired cleanup task that the cleaning robot will perform inside the isolation room. In addition the graphic simulator interfaces with the control system of the cleaning robot, thereby providing the operator with the additional vision information during operation. The cleaning paths generated from the graphic simulator are used as a command input to operate the cleaning robot. The cleanup processes of the cleaning robot are displayed in real-time on the graphic simulator. The operator can supervise and intervene the cleanup operations of the cleaning robot through the graphic simulator without seeing the interior of the isolation room through the shielded windows, thereby reducing the operator's physical and mental burdens.

### 3.3 Path generation

In this work, we used a left-turn method and horizontal searching method in generating the path of the teleoperated cleaning robot. A user can choose either the left-turn method or horizontal searching method before starting the cleaning robot path generation. The left-turn method is to search for a possible moving direction in the order of left, forward, right, and backward. The horizontal searching method is to search for a possible moving direction in the order of forward, downward, backward, and upward. Fig. 4 shows an example of generating the cleaning robot path using the left-turn method. In the figure, the arrow in the small box represents the heading direction of the robot. As the robot moves, it sweeps small boxes. Numbers are assigned to all the boxes swept by the robot to differentiate the swept and non swept area. The number starts from a big one and is reduced by one as the robot moves. Since the robot cannot turn to the left and move forward (Fig. 4(a)), it turns to the right. In Fig. 4(b) and (c), since the robot cannot turn to the left, it keeps moving forward up to the point shown in Fig. 4(d). In Fig. 4(d), since the robot cannot go forward any more, it turns to the right. Then, the robot moves forward to the point shown in Fig. 4(e) since it cannot move to the left. As the robot arrives at the point shown in Fig. 4(f), it cannot find a way to move further.

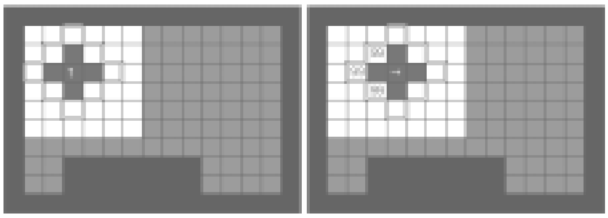
If a robot path is generated only either by the left-turn or by the horizontal searching method, there will be some regions swept twice by the robot. Thus, we develop a scheme to improve the algorithm's efficiency by minimizing the possibility of sweeping the same spot twice. This scheme is to assume that the robot moves forward, backward, left, and right by one step at the current position. The assigned values of the small five boxes occupied by the robot are then summed up. This process is performed repeatedly as the robot moves. After summing up all of the five values assigned in each direction, the robot moves to the direction having the lowest value among them. In Fig. 5, for example, when it is assumed that the robot moves to the left by one step, a big number is assigned since there is an obstacle. When it is assumed that the robot moves to the right by one step, the summed value is 296. For the assumption of the robot movement upward by one step, the summed value is 495. For the assumption of the robot movement downward by one step, the summed value is 178. Thus, the robot moves downward at the current position since it has the lowest summed value. In this way, the robot path is generated by searching for a moving direction of the robot. Whenever this scheme cannot find a moving direction, the left-turn or horizontal search method is applied to find a moving direction for the robot. If the robot arrives a spot at which the robot cannot find a way to move, it is also necessary to move the robot to an unswept place. A* algorithm [7] is then used to search for the closest unswept place and move the robot there.

## 4. MOCKUP TESTS

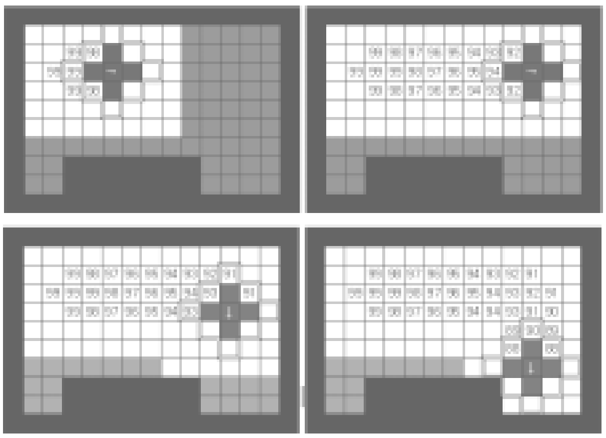
### 4.1 Remote operation

The teleoperated cleaning robot developed in this work has been tested to verify its performance and capabilities in the mockup of the isolation room at the DUPIC test facility. Fig. 6 shows the mockup test environment of the cleaning robot for a cleanup operation. The human operator and control console are located outside of the mockup of the isolation room, and the cleaning robot located inside it. As the same as in a real application, the cleaning robot is powered and controlled via a tether. This form of power and control was selected because powering the cleaning robot via a tether allows for reliable operations of an unlimited duration and eliminates the need for batteries. In addition the transmission of the control and power signals through a tether ensures the reliable control of the cleaning robot, regardless of the remote distance or barrier between the cleaning robot and the operator.

The cleaning robot is operated either by the manual control or by the autonomous control. The graphic simulator is activated both in the manual and autonomous control mode. As shown in Fig. 6, a dashed line denotes the manual control, and a solid line the autonomous control. In the manual control mode the handcontroller attached on the control



(a) turning to the right (b) moving forward



(c) moving forward (d) turning to the right

(e) moving forward (f) the end of the path generation

Fig. 4 An example of generating the cleaning robot path using the left-turn method.

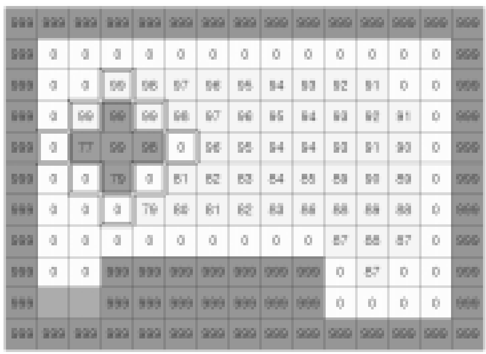


Fig. 5 A scheme for searching for a moving direction of the cleaning robot.

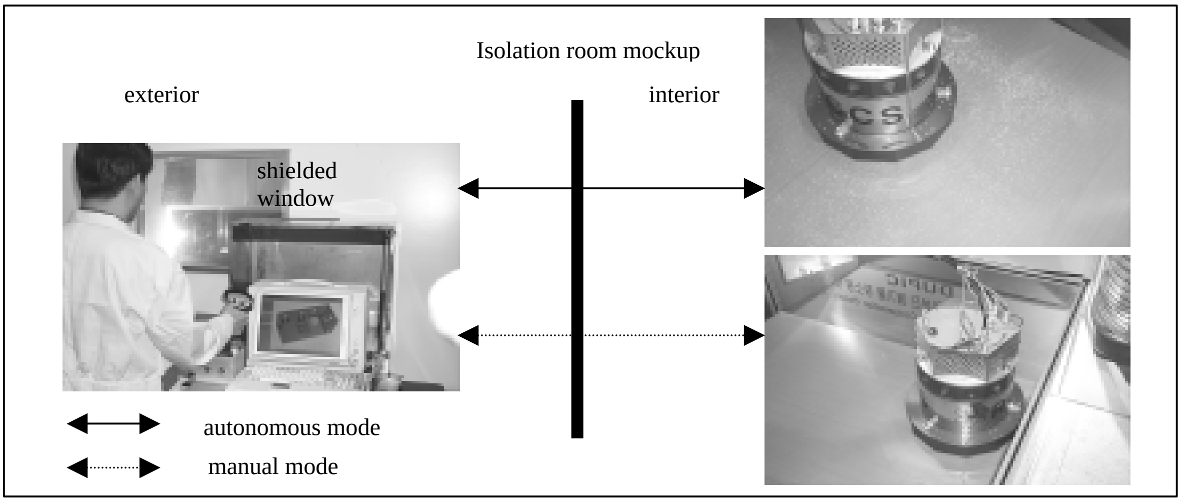



Fig. 6 The mockup test environment of the cleaning robot for cleanup operations.

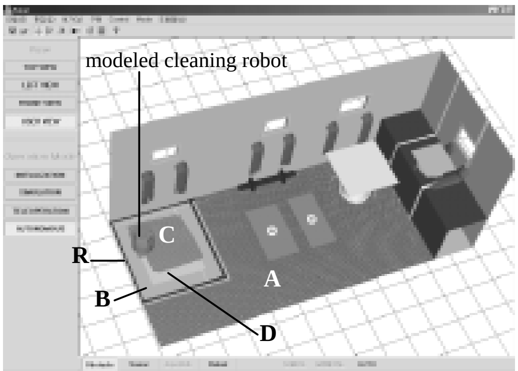



Fig. 7 The cleanup status of the teleoperated cleaning robot displayed on the graphic simulator.

console is a man-machine interface device that allows for interaction between the operator located outside the isolation room and the cleaning robot located inside the isolation room. The operator manipulates, via the handcontroller, the robot to move it into the desired locations for cleanup. The operator then controls the control knobs to activate both the cleaning and collection modules. In the autonomous mode the robot, at the initial stage, identifies its current position and steering direction before it moves. The robot then moves to clean the floor following the path generated from the graphic simulator. In the autonomous mode the robot, however, has limitations of the cleaning area in terms of mobility because of the nature of the ultrasonic sensors installed on the robot. The maximum closest distance that the cleaning module of the robot can reach to the inside wall of the isolation room is about 20 cm apart. Such an inaccessible area around the inside wall in the autonomous mode can be cleaned by switching the control mode to the manual and, via a handcontroller, controlling the robot to move close to the wall edge. For both the manual and autonomous operations the cleanup status of the robot is always displayed on the graphic simulator in real-time.

Fig. 7 shows the cleanup status of the floor performed by the cleaning robot, which is displayed on the graphic simulator. On the graphic simulator the entire area of the floor surface of the isolation room to be cleaned is represented by ‘A’ at the very beginning of the cleanup. ‘R’ in the shape of a rectangle represents the test area to be cleaned, which corresponds to the floor of the isolation room’s mockup. The area that, in the autonomous mode, the cleaning robot cannot reach is depicted as ‘B’. ‘C’ denotes the completely cleaned area of the floor surface. As the cleaning robot moves, the trail that the robot passed on the floor is changed to ‘C’, thereby differentiating the swept, ‘C’, and unswept areas, ‘D’. The main issue of importance is to clean the entire contaminated floor surface without leaving any unswept spot. Thus, the swept and unswept area can be clearly identified from the graphical simulator. In both the manual and autonomous modes, the operator can monitor all the cleanup and collection operations of the cleaning robot both through the shielded windows and the graphic simulator.

**4.2 Remote maintenance**

The submodules of the teleoperated cleaning robot can be assembled or disassembled in a remote manner. The failed submodules can be repaired or replaced for new ones when necessary. Fig. 8 shows the scenario of assembling each submodule of the cleaning robot in sequence at the mockup of the isolation room. The mobile module (B) is just placed on the top of the cleaning module (A) by guide brackets (1) and index stripe (4). The mobile and cleaning modules are then put together by fastening three bolts (2) (Fig. 8(b)). The sensing module (C) is placed on the top of the mobile module (Fig. 8(c)), and the collection module (D) and the cover module are placed on the top of the sensing module in sequence by guide bars (3) and index stripes (4) (Fig. 8(d, e)). Finally, fastening three bolts (5) completes the assembly of all the submodules, thereby forming the cleaning robot. The disassembly can also be conducted in reverse order of the assembly in a remote manner.

The used filter box can also be remotely exchanged for new one. Fig. 9 shows the procedures of exchanging a used filter box by means of master –slave manipulators installed at the mockup of the isolation room. The upper part in Fig. 9 shows the separation of the used filter box from the collection module. The lower part in Fig. 9 shows the insertion of a new filter box into the collection module. In a filter box exchange operation, the human operator manipulates it, via the master-slave manipulators to perform the specified tasks manually in a remote manner.

## 5. CONCLUSIONS

A teleoperated cleaning robot developed in this work was able to demonstrate the robotic application for performing cleanup tasks in a high-radiation field. The significance of this development is in providing the teleoperated cleaning robot for cleaning the contaminated floor surface of the isolation room and collecting the radioactive waste in a remote or autonomous manner without endangering the human workers. The cleanup and collection operations in the contaminated isolation room using this cleaning robot would have the benefits of improved worker safety, increased facility soundness, and a reduced personnel exposure dose rate.

## ACKNOWLEDGMENTS

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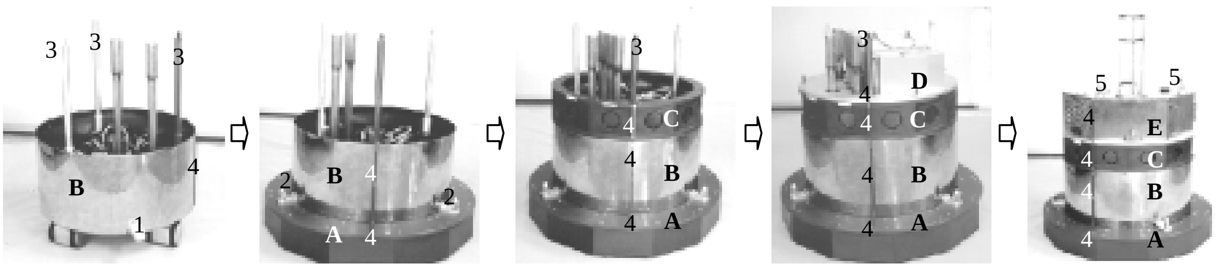


1: guide brackets, 2: bolts, 3: guide bars, 4: index stripe, 5: bolts
A: cleaning module, B: mobile module, C: sensing module, D: collection module, E: cover module
Fig. 8 The assembly of five sub-modules consisting of the teleoperated cleaning robot in a remote manner.

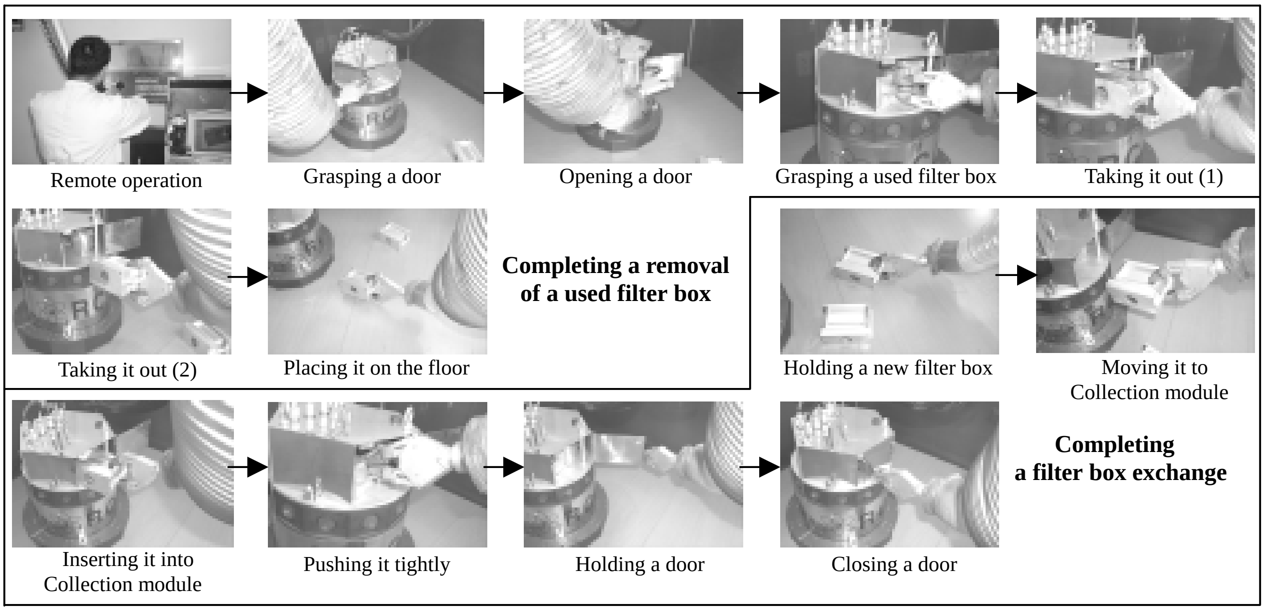


Fig. 9 The remote exchange of a used filter box of the collection module.