

Analysis of Remote Operation involved in Spent Nuclear Fuel Conditioning Process using its Virtual Mockup

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Abstract: The remote operation of the Advanced Spent Fuel Conditioning Process (ACP) is analyzed by using the 3D graphic simulation tools. Since the spent nuclear fuel, which is a high radioactive material, is processed in the ACP, the ACP equipment is operated in intense radiation fields as well as in a high temperature. Thus, the equipment is operated in a remote manner and should be designed with consideration for the remote handling and maintenance. Also suitable remote handling technology needs to be developed along with the design of the process concepts. For this we developed a graphic simulator, which provides the capability of verifying the remote operability of the ACP without the fabrication of the process equipment. In other words, by applying virtual reality to the remote maintenance operation, a remote operation task can be simulated in the graphic simulator, not in the real environment. The graphic simulator will substantially reduce the cost of the development of the remote handling and maintenance procedure as well as the process equipment, while at the same time developing a remote maintenance concept that is more reliable, easier to implement, and easier to understand.

Keywords: ACP, Remote maintenance, Virtual Mockup, Graphic Simulation, Tele-operation

1. INTRODUCTION

To deal with the rapidly increasing spent nuclear fuels, the reliable and effective management of the spent fuel has become a worldwide mission. One of the alternatives, which seems to be the most promising at this moment, is pyroprocessing. Pyroprocessing recycles the uranium resources which reside in the spent fuel as well as removing the toxic element in the spent fuel. Korea Atomic Energy Research Institute (KAERI) is also developing this process namely the Advanced Spent Fuel Conditioning Process (ACP). The ACP transforms the ceramic type uranium into a metallic form by reducing the uranium oxide by lithium in a high temperature molten salt bath while removing the high heat and radioactive sources such as Cs and Sr. In such a way, the volume, radioactivity and the heat generation of the spent fuel can be greatly reduced. Thus, the space for the disposal of the spent fuel is greatly reduced while the disposal safety is enhanced.

Currently, lab-scale tests for the ACP have been completed and the process will be installed in a shielded space of radioactivity. The ACP equipment operates in intense radiation fields as well as in a high temperature. Thus, the equipment should be designed with consideration for the remote handling and maintenance. As well as suitable remote handling and maintenance technology needs to be developed along with the design of the process concepts. To develop such remote operation technology, we developed a graphic simulator which provides the capability of verifying the remote operability of the ACP without the fabrication of the process equipment.

A conventional approach to develop the process and remote maintenance technology is achieved by a physical mockup test. The mockup is made identical to the actual process with the same scale. The main difference of the mockup and the real process is that the demonstration of the remote handling operation is made using a simulated fuel, not an irradiated fuel. The mockup test is expensive and time consuming, since the design may need to be modified to fix the problems found during the test and the equipment needs to be fabricated again according to the design modification[1-3].

To deal with this problem, we developed a graphic simulator for the ACP. And the virtual mockup of the hot cell is implemented using a graphic simulator. For the implementation of the virtual mockup, all the process equipment and maintenance devices, such as the master slave manipulators and a servo manipulator are modeled in 3-D graphics, and the appropriate kinematics are assigned. Also, the virtual workcell of the ACP is implemented in the graphical environment, which is almost identical to that of the real environment.

Using this mockup visualization of the process and various analyses have been made. Typical examples are a workspace analysis of the manipulator, a FOV(field of view) analysis of remote monitoring camera, an operator's view through the shielding windows, the collision detection and the path planning of manipulators, and the graphic simulation of the processes, etc.

2. GRAPHIC MODEL OF ACP EQUIPMENT

2.1. Overview of ACP

The objective of the ACP is to treat the spent fuel in a molten salt (LiCl) bath to remove the volatile and high-heat load fission products and to convert the spent fuel into a metallic form more suitable for disposal in a repository. The process is to treat a high radioactive material including spent nuclear fuel. Therefore, this process is conducted in a sealed facility, called a hot cell. The ACP process consists of several equipment such as a slitting device, a voloxidizer, a reduction reactor, a smelting furnace, and non-destructive assay (NDA) system, etc[4, 5].

The process flow of the ACP is shown in Fig. 1. The hot cell is divided into two areas, the process cell and the maintenance cell. The main process is carried out in the process cell. In the maintenance cell, the failed crane is repaired and the failed parts are replaced.

To operate the process and to repair the failed parts, five sets of wall-mounted master-slave manipulators and a bridge-suspended servo manipulator are used.

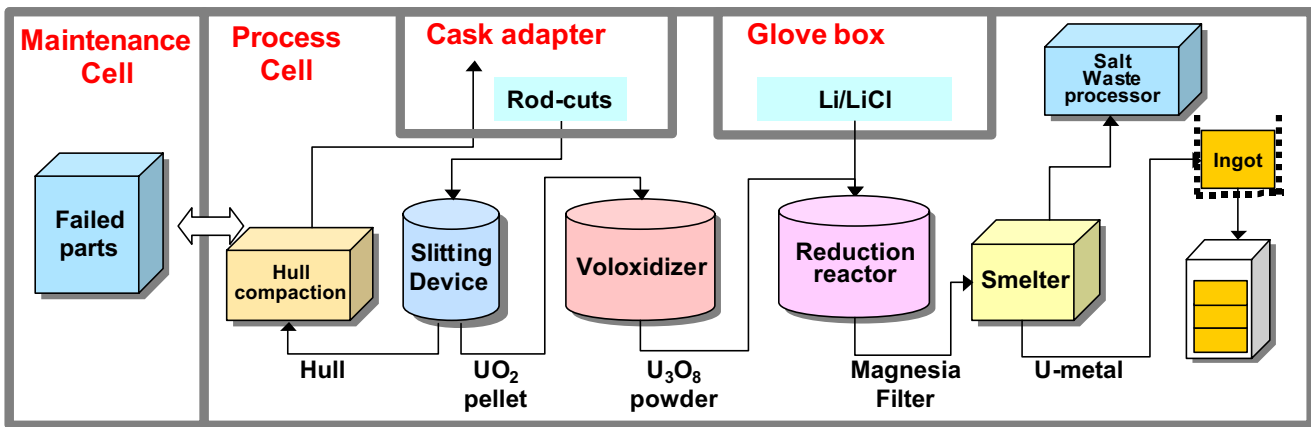


Fig. 1 Hot cell layout and the process flow of the ACP

2.2. Process Equipment

2.2.1. Slitting device

The slitting device separates the spent UO_2 Pellet from the clad tube by passing the rod cut through the 5 sets of cutter blades. Each set consists of 3 cutters distanced from each other at 120° and the distance between the centers of the blades decreases gradually as shown in Fig. 2.

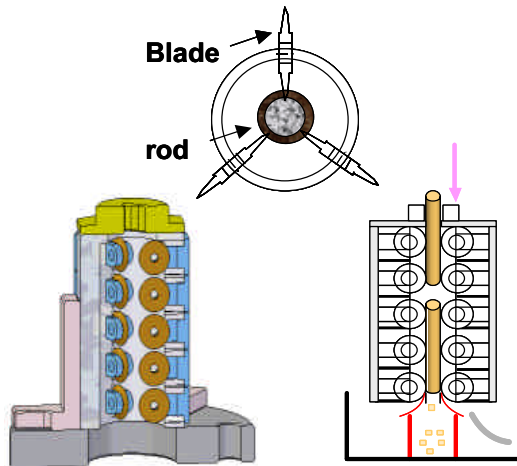


Fig. 2 Slitting device

2.2.2. Voloxidizer

The voloxidizer transforms the UO_2 pellet into the U_3O_8 powder, by heating and supplying air into the reactor. This equipment consists of a furnace, vibrator and air cylinder for moving up and down the powder collection vessel as shown in Fig. 3.

2.2.3. Reduction reactor

The reduction reactor converts the U_3O_8 powder into the U metal. The reactor consists of a furnace for heating the U_3O_8 powder and the lithium, an air agitator for mixing the lithium and the U_3O_8 powder, and a valve for exhausting the uranium and lithium solution as shown in Fig. 4.

All the parts are graphically modeled and assembled for the simulation of the maintenance operation as shown in Fig. 5.

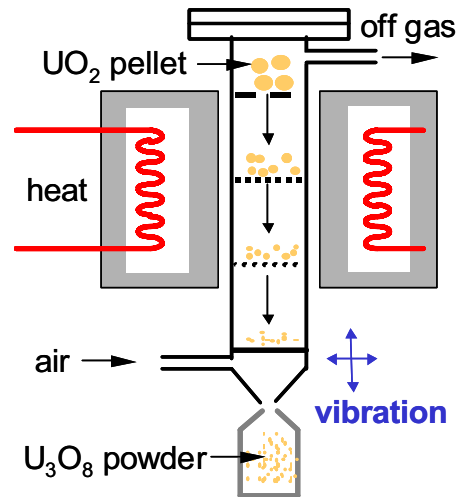


Fig. 3 Voloxidizer

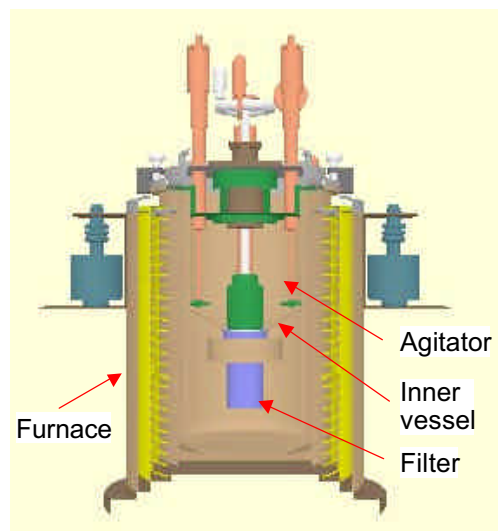


Fig. 4 Reduction reactor

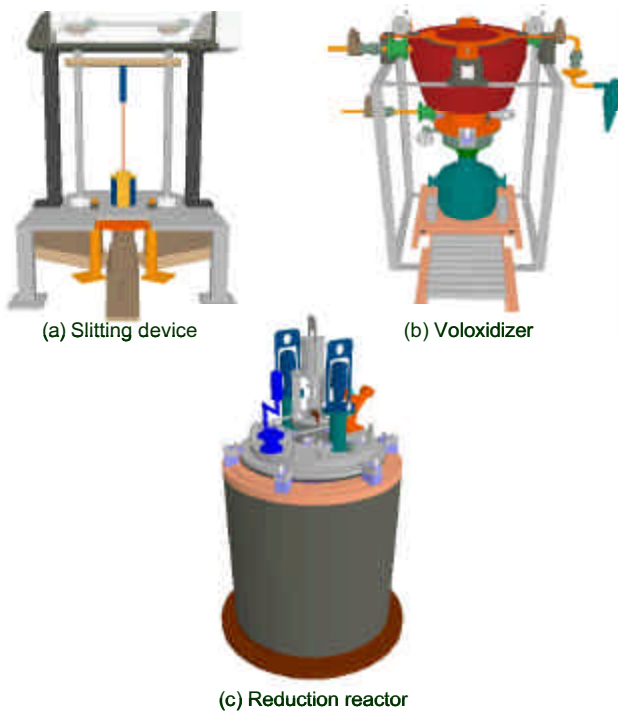
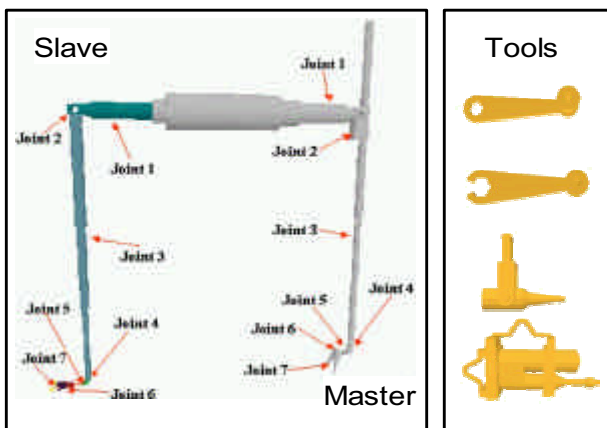


Fig. 5 3-D model of the process device for the ACP

2.3. Remote Maintenance and Handling Device

The master-slave manipulators (MSM) along with the remote tools shown in Fig. 6 are widely used as remote handling devices in the hot cell. But the MSMs are mounted on the hot cell wall, and thus the working range of the MSMs is limited to the area adjacent to the hot cell wall as shown in Figs. 8 and 9. In this regard, to cover the area out of the working range of the MSM, a servo manipulator (SM) has been developed. A telescoping tube set which moves the SM in the vertical direction sustains the SM. The tube set is attached to the trolley-girder system which provides the travel and traverse motion of the SM. In this way the SM can be located anywhere inside the hot cell. Also, three viewing cameras are installed at the girder as shown in Fig. 7 for monitoring the remote operation of the SM.



(a) Master-slave manipulator (b) Handling tools

Fig. 6 Graphic model of the MSM and the tools

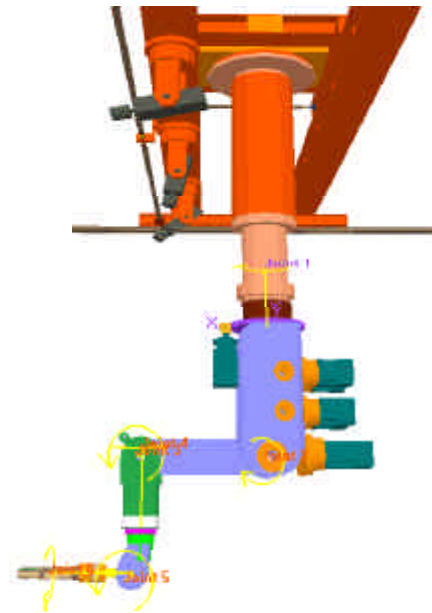


Fig. 7 Graphic model of the servo manipulator

3. VIRTUAL MOCKUP OF THE ACP

The virtual mockup of the ACP is implemented using IGRIP[6], the graphic engineering simulation tool, to analyze and define the maintenance processes of the process equipment instead of using a real mockup which is very expensive and time consuming. For the implementation of the virtual mockup, the process equipment and maintenance devices are modeled in 3-D graphics, and the appropriate kinematics are assigned as described earlier. Also, the virtual workcell of the ACP is implemented in the graphical environment, which is almost identical to that of the real environment. Fig. 8 shows the virtual mockup of the ACP. Using this mockup visualization of the process and various analysis can be made. Typical examples are a workspace analysis of the manipulator, a FOV analysis of remote monitoring camera, an operator's view through the shielding windows, the collision detection and the path planning of manipulators, and the graphic simulation of the processes, etc.

4. ANALYSIS OF THE REMOTE OPERATION

4.1. Analysis of MSM workspace

Using the virtual mockup, the workspace of the MSM in the hot cell is analyzed. Also, for the dedicated maintenance operation, the detailed workspace of the MSM is analyzed in accordance with the position and orientation of the manipulator end effectors. And the parts of the equipment that are located outside the MSM's workspace are specified.

Even though parts of the equipment are located inside the workspace of the MSM, there may be the case that these parts cannot be reached by the MSM because some of the joint limits of the MSM are exceeded as shown in Fig. 9(a). Also, even though some parts are located inside the workspace of the MSM, according to the posture of the MSM and the orientation of the end effectors, they cannot be reached by the MSM as shown in Fig. 9(b).

In such a case, appropriate means for the maintenance should be provided by using the other maintenance devices, such as a servo manipulator.

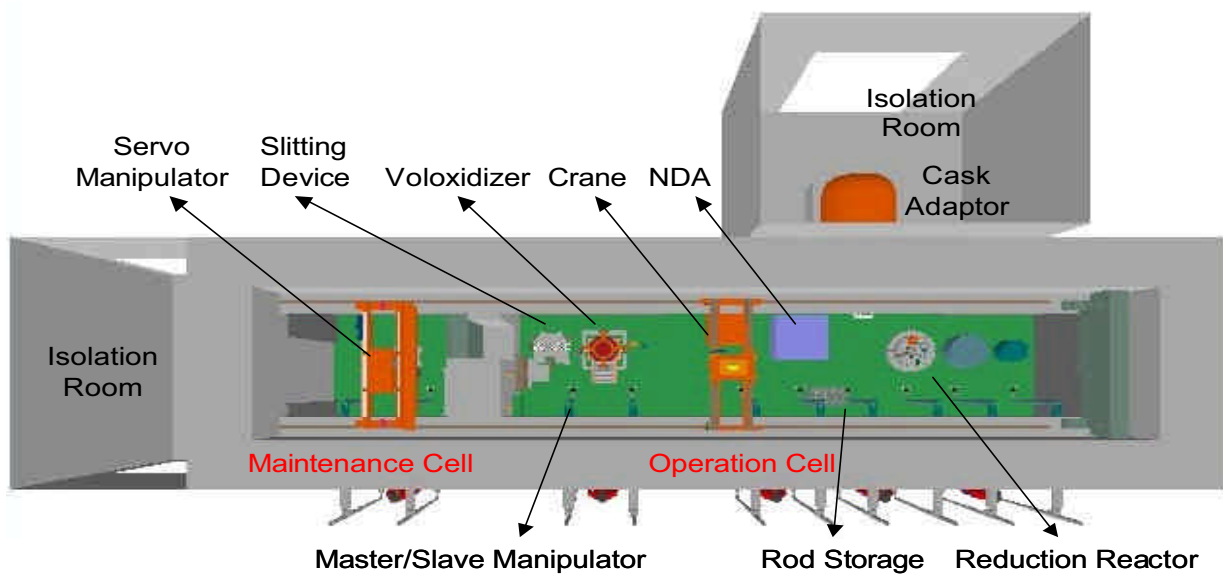
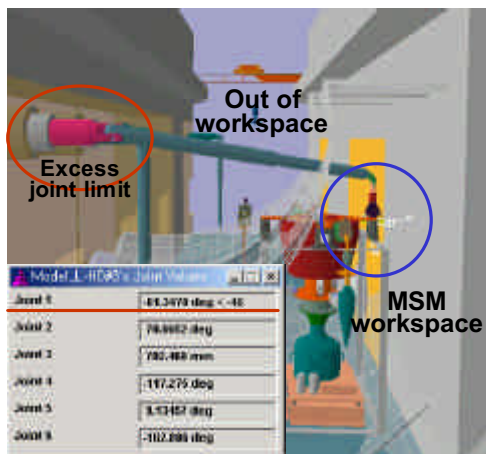
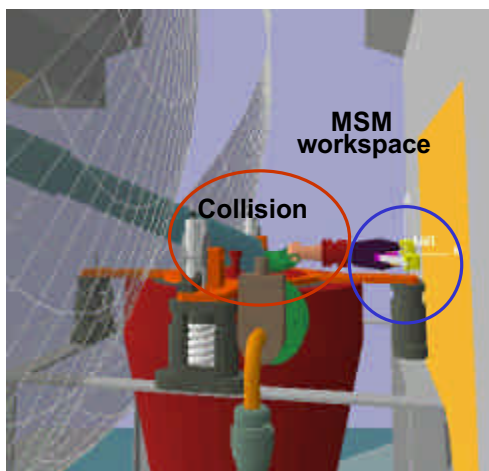


Fig. 8. The virtual mockup of the ACP



(a) Joint limit excess



(b) Wrist collision

Fig. 9 MSM workspace configuration

4.2. Analysis of the Operator's view

A clear operator's view is very important for the remote operation. The operator's view through a shielding window, which is made of lead glass is analyzed. Fig. 10 shows the viewing area through the window based on the normal view of the window in the virtual mockup. As shown in the figure, there are some areas outside the normal view range in the hot cell. It is called the extreme view area. To observe the process in this area the operator should come closer to the hot cell wall but still a clear view is not provided. And this makes uncomfortable for the operator to grip and manipulate the master manipulator. So, to monitor the process in this area, additional viewing devices, such as CC TVs in the hot cell, are required.

Even though the process is located within the normal view area, some parts may be invisible if the parts are located at a higher position than the operator's eye as shown in Fig. 11(a). In such a way the operator's view can be analyzed using the virtual mockup and thus the optimal layout of the process can be obtained.

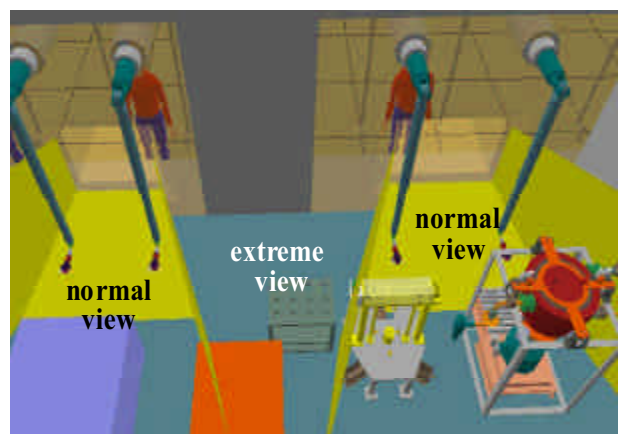


Fig. 10 Operator's view through the shielding windows

4.3. Analysis of the Remote Maintenance Operation

4.3.1. Parts to be maintained

To demonstrate the remote maintenance concept using the virtual mockup, we selected the vibrators of the voloxidizer as the parts to be replaced for instance. Fig. 11 shows the MSM accessibility to the vibrators and the operator's view through the shielding window. As seen in the figure, the MSM cannot reach these parts due to the joint limit of joints 1 and 3, and the operator's view is not clear.

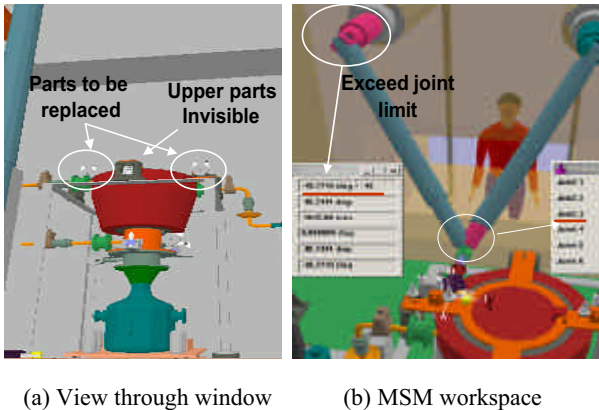


Fig. 11 Parts to be maintained and the MSM accessibilities

4.3.2. Path planning

The collision-free path planning method of the servo manipulator is suggested using the virtual mockup. The method is to find the optimal path for the manipulator using the function of the collision detection imbedded in the virtual mockup. Fig. 12 shows the procedure of the path planning to obtain the optimal path in the hot cell.

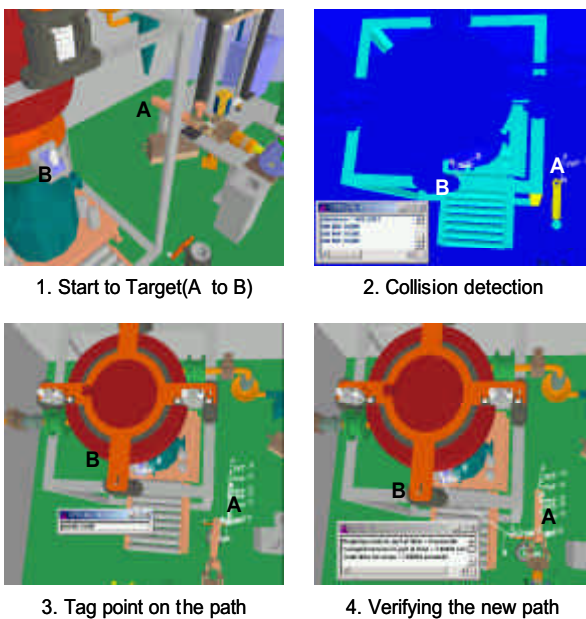


Fig. 12 Procedure of the path planning

4-3-3. Operator's view.

The operator's view in a remote operation is a very important factor. In this study, to monitor the hot cell process remotely, and to obtain a clear view of the workers, a virtual display system by a virtual camera in a graphic environment is proposed.

To implement the system, Axxess in the IGRIP is used. Axxess is a flexible API (Application Programmer Interface) framework in which the user can easily integrate its own software with the IGRIP.

Fig. 13 shows the virtual display system in the virtual mockup to simulate the maintenance process. Two virtual cameras are installed near the servo manipulator and the camera view windows for these virtual cameras are implemented in the virtual mockup using Axxess. As shown in the figures, the cameras are tracing the parts and the gripper respectively. This system can monitor the hot cell operation remotely.

4-3-4. Graphic simulation of the maintenance process.

To visualize and verify the maintenance process and thus to train the operator, a graphic simulation of the maintenance process using a virtual mockup is performed. While performing the simulation, the virtual display system proposed is also displayed. As shown in Fig 14, the proposed maintenance process works good without any collision of the servo manipulator. And no severe problems were found in the virtual workcell during the simulation. It is shown that the virtual display system offers a clear view to the operators through the maintenance operation. This means that two CC TV are optimally located on the girder. The verification of the maintenance process in the real hot cell for the spent fuel management should be carried out in the future.

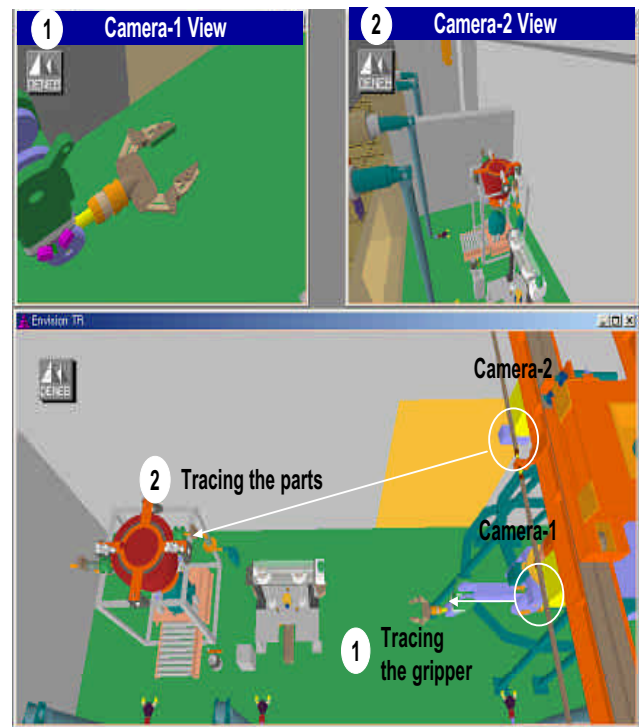


Fig. 13 The virtual display system

5. CONCLUSIONS

The equipment inside the hot cell should be optimally placed within the workspace of the MSM for a remote operation. But, due to the complexity in the hot cell, there are some parts of the equipment that cannot be reached by the MSM. In this study, a maintenance process for these parts of the equipment was proposed using virtual prototyping technology.

The virtual mockup of the hot cell process was implemented and the various analyses, such as the workspace of the maintenance devices and the operator's view through the shielding windows, were carried out in the virtual hot cell. Based on the results of these analyses, a maintenance process using a servo manipulator was proposed. And, for the verification, the graphic simulation of a proposed maintenance process was carried out.

The proposed remote maintenance process of the equipment can be effectively used in the real hot cell operation. Also, the implemented virtual mockup of the hot cell can be effectively used for analyzing the various hot cell operations and enhancing the reliability and safety of the spent fuel management.

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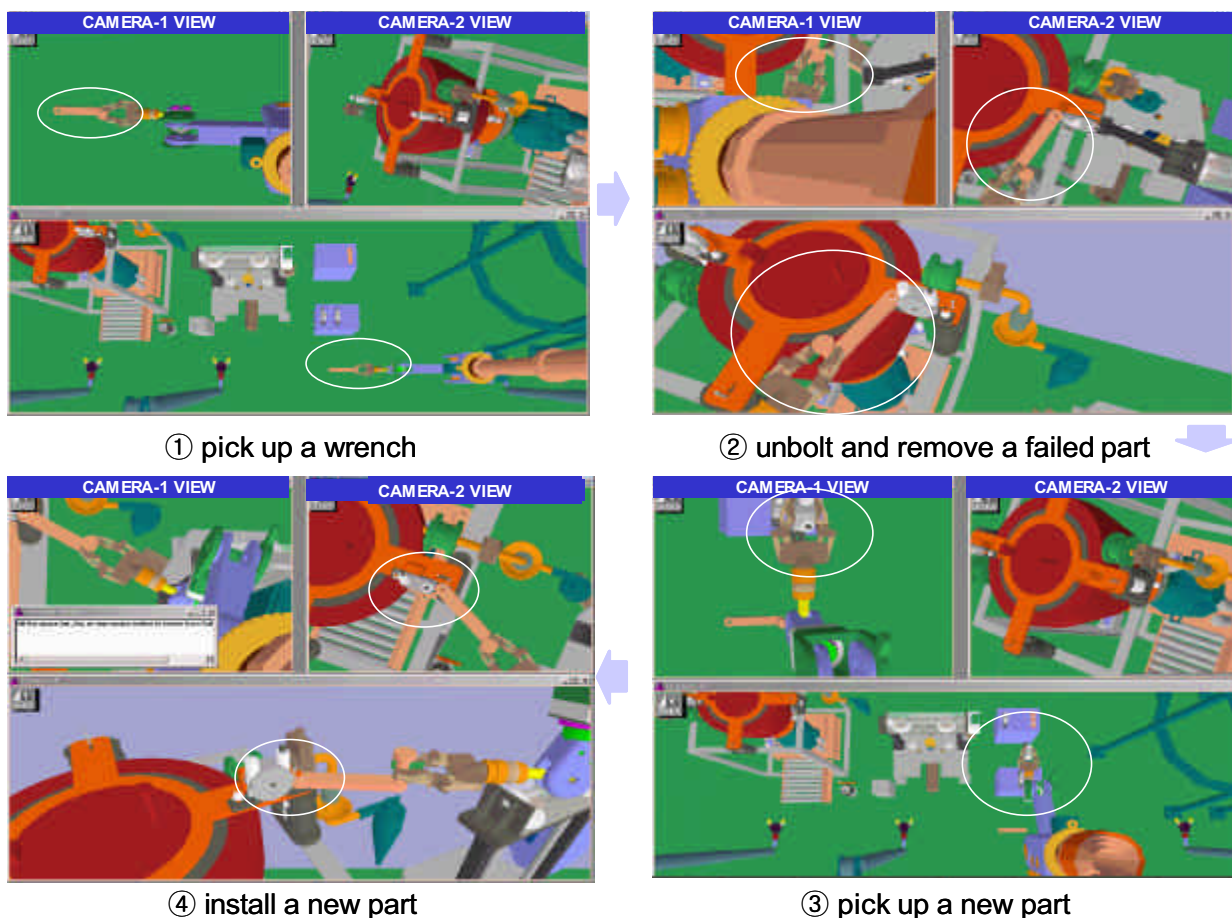


Fig. 14 Graphic simulation of maintenance process