Design of Remote Simulator for a Nuclear Fuel Cycle Facility

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ABSTRACT

The goal of this study is to provide the basic technology for an operability of a remote manipulation of an advanced spent fuel conditioning process facility. The operability and maintainability of a manipulator in a hotcell which deals with nuclear materials is one of the most important issues that should be solved in the nuclear industry. Here, we describe the design of a graphic user interface enabling an operator to model the apparatus and equipments of a Pyroprocess and explain the mathematical background in order to manipulate a virtual manipulator under a virtual environment. We also illustrate a preliminary experiment by using a 6-DOF haptic input device to establish a remote simulation.

The results show that a user deployed the apparatus at a desired position in a digital mock-up using user defined coordination module after loading the apparatus. We also found that the collision detection and force response algorithm which we applied were appropriate as we felt the force feedback whenever a virtual manipulator collided with other objects.

1 INTRODUCTION

Korea Atomic Energy Research Institute (KAERI) has been developing a strategy for implementing a pyroprocessing that includes an SFR (Sodium Fast Reactor) fuel cycle in order to achieve a more efficient and effective spent fuel management. If a pyroprocessing with the SFR fuel cycle is adopted successfully we expect to be able to reduce the disposal burden of the spent fuels. Other advantages include an effective utilization of uranium resources as well as an enhanced proliferation-resistance for the fuel cycle. KAERI has been developing an Advanced spent fuel Conditioning Process Facility (ACPF) digital mock-up system in order to obtain equivalent technology to the advanced nations. ACPF is a facility with a similar modeling and simulation concept to that of the Advanced Fuel Cycle Initiative (AFCI), which is a U.S technology development component of the Global Nuclear Energy Partnership (GNEP). Several laboratories under the DOE in the U.S have developed a simulation system such as a Simulation Enabled Safeguards Assessment Methodology (SESAME)[1], a Simulation Institute for Nuclear Energy Modeling and Analysis (SINEMA)[2], and a Verifiable Fuel Cycle Simulation (VISION)[3].

We conducted research in order to improve the efficiency of a remote operation in an ACPF digital mock-up such as the development of an interface module for an effective application of a digital mock-up[4] and a real-time graphic simulator to monitor the spent fuel dismantling devices [5]. But simulations that depend on 3D graphics are limited to the
analysis of an accessibility and operability of a manipulator. This article proposes a scheme to enable an operator to improve a remote manipulation by using haptic which is a force feedback device. Pyroprocessing, that can deal with a spent fuel requires a high manipulator skillfulness of a human operator, which is one of the most important factors to raise the productivity of uranium. A human operator, has to observe the inner side of a hotcell where many ‘blind-spots’ exist through a lead grass window has many obstacles. For this reason we have been developing technology which can analyze a manipulator’s behavior more realistically and scientifically.

2 RELATED WORKS

This section reviews the current status of a remote manipulator, haptics, and virtual reality to improve the quality of a validation and test with respect to a maintenance procedure in the Pyroprocess.

Mechanical Engineering Laboratory (MEL) in Japan developed maintenance technologies for a multi-robot collaboration in remote environments by using the internet and robotics. This system consists of a web-based mobile manipulation, a local master station, a multimedia communication server, and an on-line graphic simulator to perform a maintenance work where a fixed robot grips the holdfast on the bolt-on lid while another mobile based robot approaches it to loosen and remove the bolt on the lid in a plant mock-up[6]. In the manufacturing industry, there has been efforts to develop a virtual simulator to validate control programs (PLC) visually[7]. Application research on a remote manipulation has also been undertaken in a virtual orthopedic surgery training simulator[8]. A force feedback device is advanced technology to redouble the simulation effects to improve the sense for a real situation in a virtual environment as well as a teleoperation and a hazardous environment.

CEA LIST has been developed as a real time simulator for a maintenance task with a force feedback in an immersive environment.[9]. In remote operation technology for a spent nuclear fuel facility, COGEMA and CEA developed a telemanipulator which has been applied in the decommissioning area[10]. SCK.CEN developed an IVIM (In-Vessel Inspection Manipulator) and an IVRM (In-Vessel Repair Manipulator) in order to inspect and repair a failed component located within a vessel being inspected and detected [11].

3 REQUIREMENTS AND SYSTEM ARCHITECTURE

There are many requirements to analyze the remote operability of the Pyroprocess under a virtual environment. Firstly, a user must have an ability of a 3D modeling of the Pyroprocess facility and apparatus with a three dimensional graph in order to construct a virtual environment. Secondly, a system should possess the function of amending the apparatus which has been designed and to interconnect the force feed-back input device and the virtual environment. Thirdly, a user should be able to deploy the apparatus at a desired location after loading the VRML files. Finally, a human operator must be able to establish a haptic rendering and a graphic rendering in order to analyze the remote operability of the apparatus by using haptic. For implementing a simulator which is composed of various modules, we produced a relevant system architecture (Fig. 1).

The system begins with loading the Pyroprocess facility and apparatus files which was made by 3D CAD. Joint information of the MSM (Master Servo Manipulator) and the mechanical properties use a scene graph DB. We designed user defined coordination module in order to deploy the apparatus and equipments when users want to move them to a desired position within a desired direction. And also, we designed a GUI which enables a user to select an I/O device like a joystick, haptic, and an external interface device. The system launches a simulation when a user selects an input device in a plug-in module. We used 3DS
MAX, SolidWorks, and IGRIP for modelling the facility and apparatus which comprises the Pyroprocess. In the haptic interface, we used PHANToM desk devices 1.5 made by Sensable Ltd, and we also used Open Haptics and Visual Studio 2005. We used Open Inventor and a CodeJock Toolkit for building a basic frame of a GUI.

**Fig. 1 Schematic diagram of a remote simulator**

### 4 DESIGN OF A VIRTUAL ENGINEERING ENVIRONMENT

#### 4.1 MSM Modelling and Haptic Rendering

The ACPF process undertake an operation and maintenance task by using the MSM and BTSM (Bridge Transported Servo Manipulator). We only modeled the MSM because both of them are very similar to a working condition and relevant to a gripper with 6-DOF. The reason we selected haptic was that a simulation that depends on 3D graphics have a limitation when analyzing various situations of a manipulator behavior. Especially a maintenance work that deals with nuclear materials remotely requires a high manipulator skill of a human operator. Fig. 2 illustrates the relationship between a haptic rendering and a graphic rendering in order to analyze the remote accessibility and operability of the Pyroprocess facility. Graphic rendering seeks to provide the perception of an object’s color, geometry, surface texture, and sound effects by rendering an appropriate image. Haptic rendering seeks to provide the human operator with the appropriate force feedback to feel the geometry, surface, and material property of an object. We reviewed a couple of algorithms related to a haptic rendering; the collision detection algorithm uses position information collected through sensors to find collisions between objects and an operator action, the force response algorithm computes the interaction forces between an operator and the virtual objects involved in a collision, and the control algorithm collects the interaction force information from forced responses and supplies them to the operator through the haptic device while maintaining a stable overall behavior.

#### 4.2 Analysis of the Inverse Kinematics

We should know the 6-DOF movement of a gripper functions in order to check on an interference between the MSM and a device. To acknowledge the 6-DOF, we have to calculate the angle of the joints with input for the position and orientation of the MSM in a Cartesian space. Fig. 3 describes the coordination of a gripper and a joint of the MSM. 6-DOF of the force feed-back devices corresponds to x6-y6-z6 of the coordination in the figure. Table 1 shows the parameters along with the inverse kinematic chain developed by Denavit-
Hartenburg. In the force feedback input device, it is difficult to map it with a one-to-one ratio because of a difference between the manipulator and the kinematics. In this case it is necessary to calculate the forward kinematics for the end-effector position, orientation, and to calculate the inverse kinematics for a joint angle.

| Table 1. Denavit-Hartenburg parameters for MSM |
|-----------------|-----|-----|-----|
| \( \theta \) | \( d \) | \( a \) | \( \alpha \) |
| 1   | \( \theta_1 + 90 \) | 537.5 | 0   | 90 |
| 2   | \( \theta_2 + 90 \) | 0   | 32.5 | -90 |
| 3   | 0   | 956.6+d_3 | 0   | 0  |
| 4   | \( \theta_4 \) | 73.6 | 43.8 | 90 |
| 5   | \( \theta_5 \) | 0   | 0   | -90 |
| 6   | \( \theta_6 \) | 208.22 | 0   | 0  |

The end effector position and orientation using the transformation matrix of each joint can be represented by a 4x4 transformation matrix.

\[
T_6 = A_1A_2A_3A_4A_5A_6
\] (1)

A coordinates describe the end effector position and orientation using position coordinates and the relative-axis(Euler angles) is defined from the transformation matrix as follows:

\[
X = [xyz\phi\theta\psi]^T
\] (2)

If a coordinate system of each joint is defined as \( q = [q_1q_2q_3q_4q_5q_6]^T \) which is the current robot configuration, then we obtain Eq. (3) from Eq. (2).

\[
X = F(q)
\] (3)

This equation is a forward kinematics one, which means a transformation from a joint space to homogenous coordinates. Here X is the homogenous matrix which describes the
current transformation of the end-effector frame relative to the robot base frame. The inverse kinematics is highly nonlinear and consists of \( n \) equations with \( n \) unknowns, where \( n \) is the number of joints. To determine the desired position and orientation, we have to obtain an approximate solution by using a linearization at a special joint position. For a linearization, if it assumes an infinitesimal displacement from Eq. (2), then we can obtain it as follows;

\[
\delta X = J(q) \delta q
\]

(4)

where \( J(q) \) is the Jacobian matrix. In the case of a 6-DOF manipulator, joint motions required to achieve a specified end-effector motion are locally unique for nonsingular configurations. For this reason, we can calculate the infinitesimal displacement of a joint as follows:

\[
\delta q = J(q)^+ \delta X
\]

(5)

where \( J(q)^+ \) is the pseudo-inverse of the Jacobian, \( \delta q \) is an 6-dimensional vector of the Cartesian components of the end-effector with reference to the base coordinates, and \( \delta X \) is a vector of a joint. Eq. (5) can be applied to a redundant manipulator and can be described by a minimum joint angle in order to satisfy the infinitesimal displacement of the end-effector according to a pseudo-inverse characterization.

5 EXPERIMENTS

We carried out preliminary experiments about an interface between an operator and a haptic device in order to analyze the remote accessibility and operability of the manipulator in a virtual environment. We choose a voloxidizer of the Pyroprocess devices for an experiment. We also drew a scenario for repairing a broken part by using Haptic. The goal of the experiment was to establish if the apparatus which was produced by 3D CAD could be deployed at a desired location and also to verify if a collision detection could be achieved for a collision with other objects and to see if a virtual MSM could access a lever. The scope of the experiment is a case for the MSM to access the lever and manipulate it by moving up and down. Figure 4 depicts the lever of the Vol-Oxidizer.

6 RESULTS AND DISCUSSION

We successfully implemented a Graphic User Interface that enables a user to deploy facilities and devices within the Pyroprocess under a virtual space. Figure 5 shows a scene which deployed the Vol-Oxidizer and the MSM at a desired position in a digital mock-up. The left picture represents the MSM, Vol-Oxidizer and Pyroprocess mock-up which was modeled by 3D CAD. We confirmed that the GUI comprised a menu-bar, scene graph module, and a property module which describes the properties of the nodes. It was proven that the simulator could satisfy the basic requirements to minimize the time consumption and economical loss due to a mistake during a deployment of devices in the Pyroprocess. We found that the collision detection and force response that we applied were appropriate as we felt the force feedback whenever the MSM collided with other objects. And also, we visually identified where a collision happened whenever it bumped against other objects.
CONCLUSION

In this paper we present our design of a Graphic User Interface that enables user to model a digital mock-up facility easily by using object-oriented language. We solved the position, orientation, and the angles of the joints which were calculated by inverse kinematics and forward kinematics in relation to the 6-DOF of the manipulator in a cartesian space. We successfully completed basic research about the interface between a human operator and haptic. A collision detection could be detected well during a collision with other objects and the force feedback response could also be felt from the force feedback whenever bumping against other objects. We carried out a preliminary experiment in order to confirm that verify all the components could be running normally.

The results confirmed that a user can implement several modules which are needed to build a digital mock-up in the design stage and to analyze a remote accessibility and operability in the maintenance stage. And, also a user can arrange the apparatus and equipment correctly at a desired position.

We are going to reinforce a haptic rendering. When all the arms of a manipulator collide with other objects a human operator should be able to detect a collision and feel the force feedback. A Pyroprocess simulator is a very useful tool to apply to an operator’s discipline with respect to an operation and maintenance task.

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REFERENCES


