Design of a Bridge Transported ServoManipulator System for a Radioactive Environment

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Abstract: The KAERI Spent Fuel Remote Technology Development (SFRTD) Department is developing the remote maintenance and repair equipment, which is used in a hot cell in an intense radiation field, as part of a project to develop the Advanced spent fuel Conditioning Process (ACP). Although several mechanical master-slave manipulators (MSMs) is mounted on the hot cell wall, their reach will be limited and cannot access areas for all the ACP equipment maintenance. A Bridge Transported ServoManipulator (BTSM) has been designed to overcome the limitation of access areas that is a drawback of MSMs for the ACP equipment maintenance. The BTSM system consists of four components: a transporter with telescoping tubeset, a slave manipulator, a master manipulator, and a remote control system. The BTSM system has been designed by Solid Edge that is a 3D computer-aided design (CAD) software, except for the remote control system. The master manipulator and the slave manipulator are kinematically similar in design, except for the handle and the tong, respectively. The manipulators have 6 degrees of freedom (DOF) plus the jaws motion. The transporter has traveling, traverse, and hoisting motion to position the slave manipulator.

Keywords: Mechanical master-slave manipulators, Bridge Transported ServoManipulator, Telescoping tubeset, Hot cell, Maintenance, 3D CAD

1. INTRODUCTION

This paper describes a Bridge Transported ServoManipulator (BTSM) system, which has been designed at the KAERI (Korea Atomic Energy Research Institute) Spent Fuel Remote Technology Development (SFRTD) Department. The BTSM system is being developed to remotely maintain the Advanced spent fuel Conditioning Process (ACP) equipment in a radioactive environment. But, it can be used for other purposes in nuclear engineering and non-nuclear applications as well.

As the cumulative amount of the spent fuel increases, the reliable and effective management of spent fuel becomes a worldwide mission. At KAERI considerable R&D effort is being made to develop a management technology that will enhance environmental friendliness and proliferation resistance as well as maximize the use of available energy resources. To this end KAERI is developing the ACP as a pre-disposal treatment process for spent fuel [1]. The ACP equipment must operate at a hot cell facility in an intense radiation field and be remotely maintained by manipulators.

Mechanical master-slave manipulators (MSMs) have been widely used in the hot cell. However, there are disadvantages to this type of manipulator. Since the master and the save are directly connected, the operator is required to remain in close proximity to the working environment, and the volumetric coverage of the slave manipulators is limited because the system must be mounted on the hot cell wall. The ratio of slave to master forces is fixed at about 1:1, so the slave can apply forces only within the range of human capabilities.

In this regard, a servomanipulator mounted on an overhead bridge is a preferred option for all the ACP equipment maintenance. It can overcome the limitation of access areas and the ratio of slave to master forces that are drawbacks of MSMs, so the KAERI SFRTD department has designed a Bridge Transported ServoManipulator system. The BTSM system consists of four components: a transporter, a slave manipulator, a master manipulator, and a remote control system with control desk and control console. The BTSM system has been designed by Solid Edge that is a 3D Computer-Aided Design (CAD) software, except for the remote control system. The master manipulator and the slave manipulator are kinematically similar in design, except for the handle and the tong, respectively. The manipulators have 6 degrees of freedom (DOF) plus the jaws motion. To provide bilateral-positioning control with force feedback, seven axes of the manipulators are driven by electrical servomotors. The designed manipulators are the smallest size compared with that of the existing replica type of master-slave servomanipulators. And the slave manipulator has the biggest handling capacity, 15 kg, compared with the size of the existing slave manipulators. The transporter, which consists of the bridge, the trolley, and the telescoping tubeset with an interface system, is located at a hot cell to position the slave manipulator. The slave manipulator is mounted on the telescoping tubeset via the interface system. The master manipulator is mounted on the telescoping tubeset attached to a fixed support at operation area outside the hot cell. The manipulator control system is located around the master manipulator.

This paper will focus on the design requirements and design activities of the BTSM system.

2. DESIGN REQUIREMENTS

The hot cell dimension of the ACP is 11m (L) x 2m (W) x 4.3m (H). The bridge, trolley, and telescoping tubeset are needed to horizontally, laterally, and vertically position the slave manipulator inside the cell. As recovery purpose for failure of a single drive, they should have redundant drives. Also, their drives should be continuously controlled with travel speeds of less than 10 m/min. Accounting for the distance of 2.47m between the bridge rail and working table, the maximum height, 1.2m, of the ACP equipment on the working table, and the height of the slave manipulator to be designed, the length of the fully retracted/extracted telescoping tubeset should be determined. The telescoping tubeset should have a handling capacity of more than 100 kg. The interface system is needed to remotely detach the slave manipulator from the tubeset for maintenance using MSM. The motor parts of the slave manipulator should be disassembled from the body of the slave manipulator for maintenance using MSM. The slave manipulator and the master manipulator should have 6 DOF plus the jaws motion. The reach of the manipulators and the velocity of the end-effector tip should be less than 1 m and more than 1 m/sec, respectively. The continuous load capacity and the weight of the slave manipulator should be more than 10 kg and less than 40 kg, respectively. Considering the space constraint of the ACP hot cell, the BTSM system inside the cell should be compact and the location of cameras that provides the viewing capability of the cell should be optimally determined. The BTSM system inside the cell should withstand a total absorbed radiation dose of 10^8 rads. The control of BTSM inside the cell should be achieved using the master manipulator with force reflection and control console.

3. DESIGN OF THE BTSM SYSTEM

3.1 The overview of the BTSM system

Fig. 1 shows the BTSM system, which has been designed for duties in inaccessible areas under remote control conditions. This system has been designed using Solid Edge that is a 3D CAD software. The BTSM system consists of four components: a transporter, a slave manipulator (SM), a master manipulator, and a remote control system. The transporter equipped with the slave manipulator is located at the mockup cell. The mockup cell dimension is 3.4m (L) x 2m (W) x 3.37m (H). The height of 3.37m is distance between ground and bridge rail. This dimension is same with that of the ACP hot cell, except for the length. When the operator moves the master manipulator, the slave manipulator follows the motion of the master in real time. The designed manipulator is a force-reflecting servomanipulator. As bilateral-positioning control with force feedback without a sensor technology, the BTSM system will offer tactile feedback. The operator will get feedback concerning the forces, which have occurred from the slave manipulator via the master manipulator. This force reflection enables the operator not only to watch but also to feel his work. With this, even complicated operations can be carried out, without the risk of damaging or destroying tools or objects. Remote closed circuit television (CCTV) cameras send pictures of the working environment to camera monitors for the operator to view. Since the BTSM system is operated by human operators, human-machine interface is critical to the successful utilization of such system.

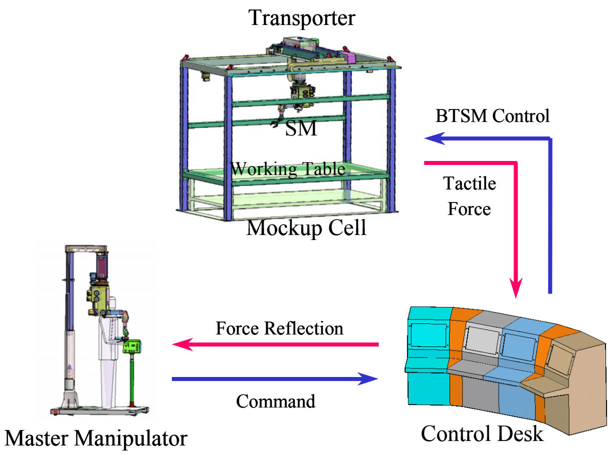


Fig. 1 A bridge transported servomanipulator system.

3.2 The transporter

Fig. 2 shows the transporter, which horizontally, laterally, and vertically positions the slave manipulator. The transporter is composed of four subassemblies: a bridge, a trolley, a telescoping tubeset (TT), and an interface system. The bridge is composed of two girders equipped with rails. The bridge is supported by two saddles with two rollers, respectively. Two of four rollers, which are driving rollers, are connected by a shaft. The drive module is mounted on this shaft. The distance between centers of the two saddles is 1.8 m, and the length of saddle is 0.78 m. Because radiation tolerant cameras tend to be large, two cameras are symmetrically mounted on girders based on space considerations and viewing angles.

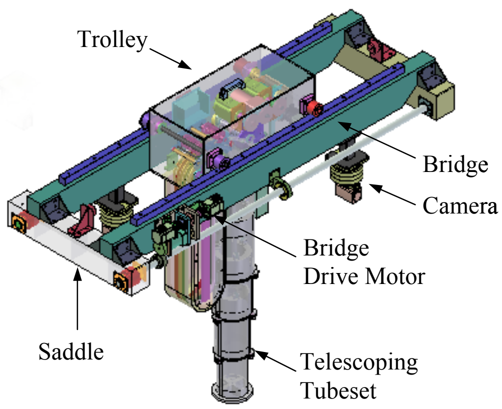


Fig. 2 The transporter with X-Y-Z motion.

Fig. 3 shows the trolley, which is composed of a box supported by four rollers. Those are connected by two shafts. The drive module is mounted on one shaft. The size of the trolley box is 320 mm x 670 mm x 310 mm. The telescoping tubeset is composed of four tubes: one fixed tube and three moving tubes. The telescoping tubeset is vertically mounted on the bottom of the trolley box. The drive module is also mounted on the floor of the trolley box. The tubeset is pulled by chain, which is driven by sprocket. The lifting motion of the tubeset is three steps with a travel of 1100 mm. The height of the fully retracted and the fully extracted tubeset without the slave manipulator is 600 mm and 1700 mm, respectively. The tubeset has a capacity of 200 kg. Each tube is guided by 6 rollers such that the telescoping tubeset can be vertically moved with hardly any play without the rotation of the tubeset. Four cables are simultaneously pushed or pulled into cable storage box along the telescoping tubeset motion. The tubeset accommodates internally four cables to transmit the electric supply to the slave manipulator.

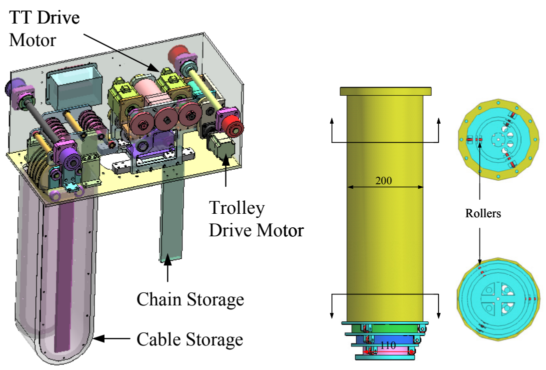


Fig. 3 The trolley with Y-Z motion.

Fig. 4 shows drive modules for the girder, trolley, and telescoping tubeset motions. Each drive module has a redundant motor for fail recovery. At normal conditions, a redundant motor is idle. At failed conditions, a failed motor is idle, and a redndant motor is driven.

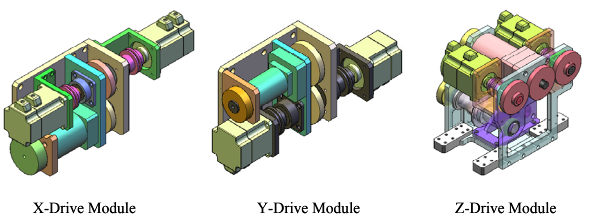


Fig. 4 Drive modules with redundant motors.

Fig. 5 shows the interface system, which remotely can attach and detach the slave manipulator from the tubeset using MSM. This system is composed of two parts: an upper part and a lower part. The upper part is mounted on the telescoping tubeset, and the lower part is mounted on the slave manipulator. At the attachment of the slave manipulator, support pin and guide pin mounted on the lower part are first inserted into the hole of the upper part by pulling up the lower part. Second, the rotation plate of the upper part is rotated using MSM and is locked by handle. The detachment of the slave manipulator is performed in the reverse of the attachment. The interface system accommodates 4 radiation tolerant electrical connectors (LEMO FAG/EGG 4B, non-latching type) between the upper part and the lower part.

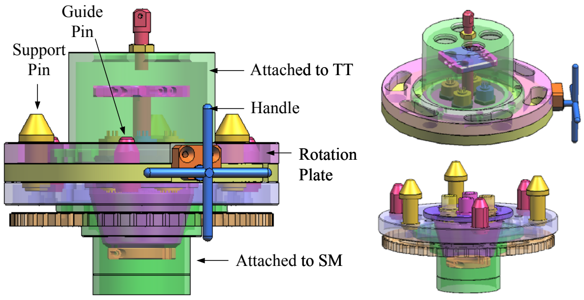


Fig. 5 The interface system.

3.3 The slave manipulator

Servomanipulators can be driven with electric motors or hydraulic actuators. Hydraulic actuators are most favorably applied in underwater or extremely heavy-duty applications. Electromechanical drive systems offer 1% of peak load force sensitivity through backdrivable gear trains and are used on most modern servomanipulator systems. As an object in space has 6 DOF, a general-purpose manipulator must have at least 6 DOF plus end-effector actuation. Additional DOFs are rarely used on servomanipulator systems as they are redundant, increase the system complexity, are difficult to operate, and are only rarely useful. Modern servomanipulators usually have a configuration similar to the human arm [2-4]. The joints are almost always rotary. Prismatic joints, though common in robots and MSMs, are rarely used in servomanipulators. The general-purpose two-fingered tong gripper is the most used end-effector in servomanipulators.

On the basis of this regard, we have designed servomanipulator system with the elbow-up stance. Fig. 6 shows the slave manipulator, which has 6 DOF plus a parallel jaw gripper. All the motors, measuring sensors, and the transmission gears of the manipulator are located in the body of the manipulator. As shown in Fig. 7, most drive units of the slave manipulator are located behind its body except for the body joint. There are no electrical cables from the body to the gripper. The radiation tolerant electrical connectors of LEMO push-pull type (FIG/PKG 2B), which are amenable to handle by MSM, are accommodated for the electrical cable connection between the body and the drive unit. The drive unit cables are connected to the lower part connectors of the interface system via the inside of the body. The body motion is driven via a concentric shaft of a drive unit and a spur gear. As shown in Fig. 8, the transmission of the motion from the upper arm motor and the lower arm motor to their joints is realized via shafts of drive units, bevel gears, and connecting rod for the lower arm joint. The transmission of the motion from a lower arm twist motor, two wrist motors, a gripper motor to their joints is realized via shafts of drive units, bevel gears, and stainless steel wires [5]. The drive units are equipped with three-phase servomotors, brakes and resolvers on the motor shafts. Potentiometers for measuring the absolute position of all axes are mounted on the shaft of second bevel gear for arm joints and spur gear for body joint. There is no direct connection between joints and motors. The length of the upper arm and the lower arm for the slave manipulator are 330 mm, respectively, and the length of the gripper is 250 mm. The body dimension is 285 mm x 230 mm x 445 mm. The weight and continuous load capacity will be about 40 kg and 15 kg, respectively. The slave manipulator is mounted on the tubeset via an interface system.

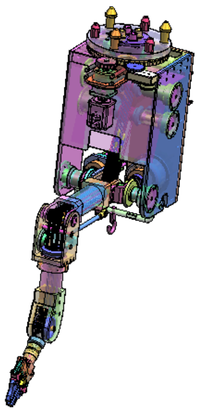
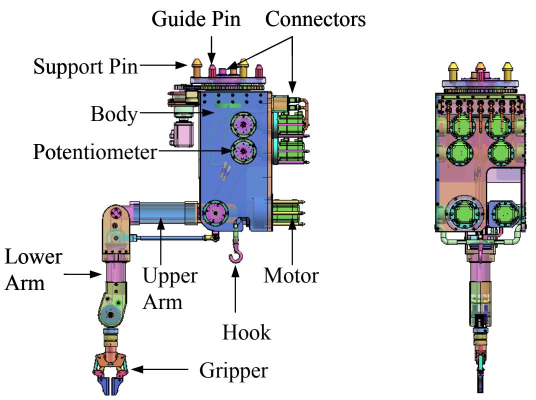
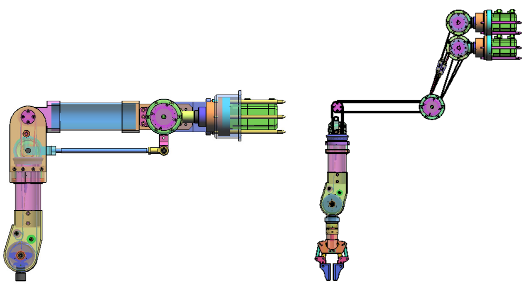


Fig. 6 The slave manipulator with 6-DOF plus a gripper.



(a) Side view (a) Back view

Fig. 7 The side and back view of the slave manipulator.



(a) Axes driven by gears (b) Axes driven by wires

Fig. 8 Drive mechanism for the arm axes.

3.4 The master manipulator

As shown in Fig. 9, the master manipulator system is composed of six parts: a floor, a column attached to the floor, a bridge of the cantilever type attached to the column top, a telescoping tubeset attached to the bridge, a master manipulator attached to the telescoping tubeset, and a control console erected to the floor side. The master manipulator is a replica of the slave manipulator. The drive mechanism of the master manipulator is basically identical with that of the slave manipulator, except for the joint 1 and the handle. The motor on joint 1 is attached to the tubeset mounted on the bridge of the cantilever type. But, the motor on the joint 1 of the slave manipulator is attached to the body of the slave manipulator. The tubeset can be manually extracted or retracted by operator with a travel of 500 mm. Because the height of the operators is different, the tubeset motion is useful of adjusting the distance between the floor and the bottom of the master arm handgrip in a nominal stance. The control console is used to move the slave manipulator and/or the transporter without operating the master manipulator.

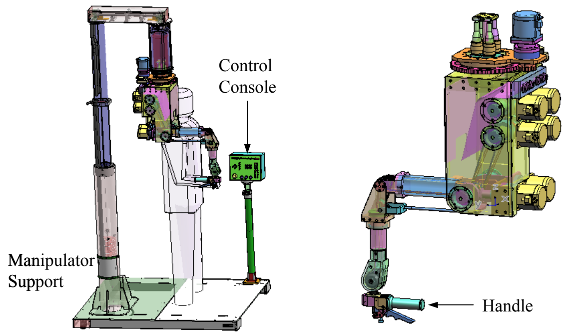
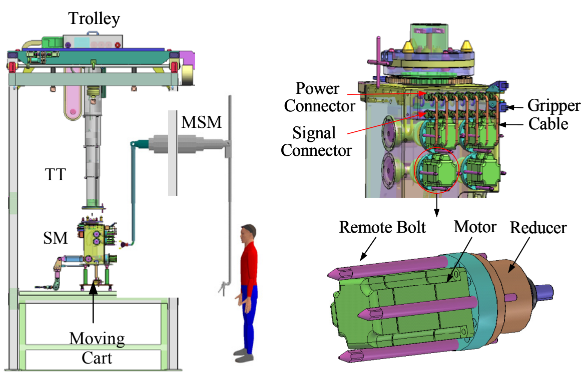


Fig. 9 The master manipulator with an additional console.

3.5 The concept of the slave manipulator maintenance

The slave manipulator has been designed for remote disassembly from the tubeset. Fig. 10 shows the concept for the slave manipulator maintenance. The slave manipulator is lowered on a moving cart in front of one of the MSM windows and detached from the tubeset via interface system using MSM. This system was previously introduced in Fig. 5. At this time, electrical connectors are simultaneously disconnected inside the interface system. At the disassembly of the drive unit, the plugs of the power and the signal connector are first pulled out of sockets by MSM, and remote bolts mounted on the drive unit are unbolted from the manipulator body by MSM.



(a) Manipulator disassembly (b) Drive unit disassembly

Fig. 10 The remote disassembly of SM and drive unit.

3.6 The remote control system

As shown in Fig. 1, the remote control system is composed of a control desk and a control console erected around the operator. The control desk involves camera monitors, motor drives, PC, and so on. The PC control system will be accomplished based on the PCI bus and Windows operating system. Multi-axis Motion Controllers (MMCs) made by SAMSUNG will control the BTSM system. The BTSM system software will be written in Borland C++ Builder 6.0 under the Windows 2000. As the operator moves the master manipulator, the slave manipulator will follow the motions of the master manipulator in real time. Remote CCTV cameras will send pictures of the working environment back to the camera monitors on the control desk for the operator to view.

Fig. 11 shows the control console, which is used to directly control the slave manipulator without operating the master manipulator, the transporter, and cameras. The control console includes a joystick and a set of control switches and buttons. The joystick controls a traveling, traverse, and hoisting motion of the transporter. Buttons and switches independently control the joints of the slave manipulator, select the camera, and control the pan/tilt/zoom/focus of the selected camera.

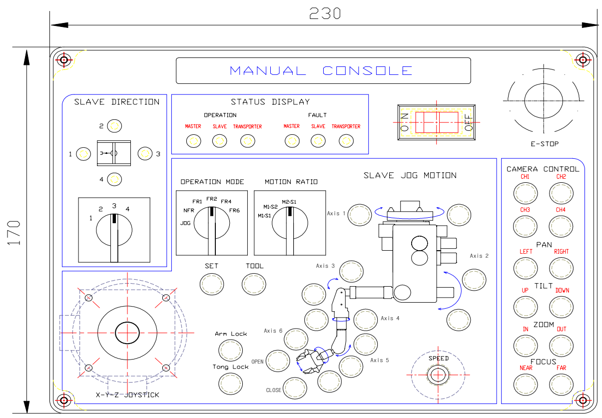


Fig. 11 The control console of the BTSM system.

4. CONCLUSIONS

A Bridge Transported ServoManipulator (BTSM) system to remotely maintain the Advanced spent fuel Conditioning Process (ACP) equipment in a radioactive environment has been designed by Solid Edge that is a 3D CAD software. The BTSM system is composed of four components: a slave manipulator, a transporter positioning the slave manipulator, a master manipulator, and a remote control system with control desk and manual control console. The master manipulator and the slave manipulator are kinematically similar in design, except for the handle and the tong, respectively. The manipulators have 6 degrees of freedom plus the jaws motion. To provide bilateral-positioning control with force feedback, seven axes of the manipulators are driven by electrical servomotors. The designed manipulators are the smallest size compared with that of the existing replica type of master-slave servomanipulators. And the slave manipulator has the biggest handling capacity, 15 kg, compared with the size of the existing slave manipulators. The slave manipulator can be detached from the telescoping tubeset of the transporter using MSM, and the drive units also can be detached from the manipulator body using MSM.

ACKNOWLEDGMENTS

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