Remote Handling Crane System for Use in Small Argon Compartment Hot-cell

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Abstract: In this paper, we describe the design of a novel crane system for use in a small argon hot-cell where only a mechanical master-slave manipulator (MSM) within the limitation is available for the maintenance of the crane. To get a practically achievable solution for the design problem, we devised a remote actuation mechanism in which the electrical parts of the crane are separated from the mechanical parts and installed inside the workspace of the MSM for remote maintenance. Even though the design concept does not provide a thoroughly sufficient solution because the mechanical parts are placed out of the MSM's workspace, the durability of the mechanical parts can be easily increased if they have a high safety margin. Therefore, the concept may be one of best solutions for our special crane system. In addition, we developed a servo-control system based on absolute positioning technology; therefore, it is possible for us to perform the given tasks more safely through an automatic operation.

1 INTRODUCTION

Crane systems are widely used to transport heavy items and hazardous materials in factories, construction spots, docks, and nuclear power plants. Three factors such as speed, accuracy, and safety, are the most important factors in crane operations in which the swing of the payload degrades all of these factors during transport operations. Therefore, intensive research works have been focused on to minimize the swing of the payload (Abderrahim, Gimenez and Balaguer, 2008).

As for the maintenance of industrial crane systems, it is possible to maintain or repair the failed unit through direct access even through the work is to be performed in a potentially dangerous high place. In a special facility, such as a "hot-cell" in which direct access by human operators is not possible due to the high radioactivity, the crane systems are considered indispensable. In this case, the maximum speed should be limited for safe operation, and remote maintainability is one of the most important design requirements. There are two approaches for the maintenance of the hot-cell crane system. First, a damaged crane is towed by an auxiliary crane installed in the upper floor maintenance room through a hatch door (Piolain, Geffard and Coudray, 2006). Second, the hot-cell crane system is moved to an adjacent maintenance area on the same floor, and then the operator performs hands-on repair of the failed unit after decontamination (Bradley, Burgess, Graves, Spampinato and Varma, 2004). In these methods, the the crane system should have redundant drives for the preparation of a failure of a normal driving line to move the crane to the maintenance area.

In this paper, we describe the design of a special crane system for use in a small argon compartment hot-cell where no auxiliary lifting system for the rescue of the crane is available.

2 DESIGN REQUIREMNTS OF CRANE SYSTEM

An Advanced spent fuel Conditioning Process Facility (ACPF) was constructed at the KAERI site as a demonstration facility of laboratory-scale pyroprocessing technology (You et al., 2009). The ACPF is an air environment hot-cell and it has two separated areas: the process cell and maintenance cell, the dimensions of which are 8.1m (L) x 2m (W) x 4.3m (H) and 2.2m (L) x 2m (W) x 4.3m (H). The wall of the hot-cell is made of thick heavy concrete

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to maintain the dose rate at less than 0.01 mSv/h in the operation area. Five pairs of lead-glass shielding windows are installed on the operation side of the hot-cell. Each window workstation is equipped with a pair of MSMs. Several batch operations have been completed using pure uranium and depleted uranium (DU).

Even though existing process equipment was equipped with a built-in argon supply system, it suffered from some problems arising from corrosion and moisture because it was installed in an air environment cell. Therefore, the necessity of an argon hot-cell was a pressing issue for enhancing the performance of the processing equipment. As a part of the refurbishment project, a redesign of the ACPF began in March 2012 (Park, Lee, Yu, Kim and Cho, 2013). An argon hot-cell will be constructed inside the existing process cell as a compartment, as shown in Fig. 1, and its volume is approximately 11% of the ACPF, with dimensions of 1.8m (L) x 2m (W) x 2.65m (H). The existing lead-glass shielding window and two sets of MSMs will be used without any modification of the argon compartment. On the other hand, a small crane system with a load capacity of 1.50 kN will be installed on the argon compartment. However, since the crane system will be installed on the ceiling of the argon compartment, the design constraints arising from facility dimensions, a lack of a remote handling device, and process operation conditions should be considered from the design stage.

As shown in Fig. 1, the MSM cannot reach the argon compartment crane, which indicates that there is no maintenance means for the crane. We established several design requirements. The first design constraint arising from the space-limited cell is that the maximum height of the crane should not exceed 300 mm. This constraint means a minimum height of the crane whose load hook can be placed over the MSM without contact.

The second design requirement is related to the operation condition of the process equipment. Since the manual operation while viewing the equipment through a shielding window may lead to mishandling due to inaccurate distance feeling, it is desirable for the crane to operate with accurate movements like a robot. Therefore, a non-slip structure is more advantageous. In addition, direct access by a human operator to a hot-cell is restrictively allowed after decontamination, or is not absolutely allowed; therefore, all mechanical parts that are installed on the ceiling should be designed with strength and durability. In addition, because the MSM is the only available remote handling system in the argon compartment, motors, sensors, and limit switches should be placed inside the workspace of the MSM, and they should be designed to provide easy attachment/detachment.

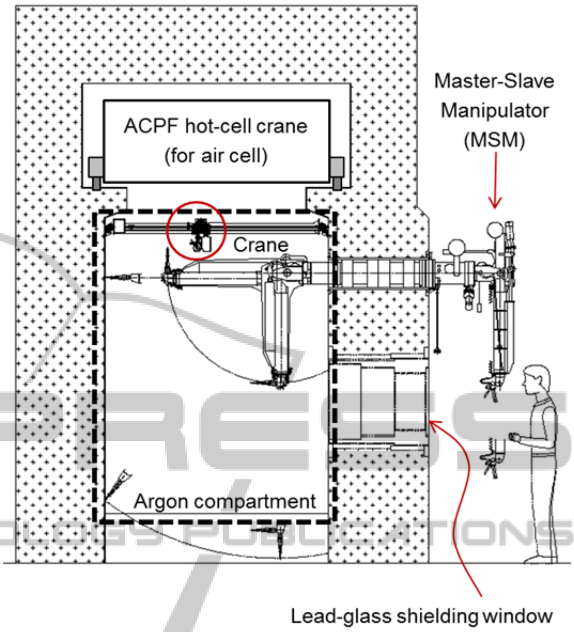

Figure 1: Cross section view of the conceptual design of the argon compartment. The dashed box indicates the argon cell that will be constructed inside the existing ACPF as a compartment.

3 DESIGN OF REMOTE HANDLING CRANE SYSTEM

3.1 Remote Actuation Mechanism

There is no way to design a crane system that throughly fulfills the design requirements owing to the space-constrained environment as well as the reach limitation of the MSM. To find the best solution for this crane design problem, we made two assumptions:

- Electrical parts (motor, sensor) have more possibilities of a breakdown than the mechanical parts.
- The durability of the mechanical parts can be easily increased if they have a high safety margin.

Based on these two assumptions, we devised a remote actuation mechanism using the transmission shaft. As shown in Fig. 2, the mechanical parts and electical parts of the crane system are separated and connected through a transmission shaft. That is, electrical parts consisting of a servomotor, a position sensor, and two limit switches, located inside the workspace of the MSM, transmit the power to the mechanical parts. Even though the design concept does not provide a thoroughly sufficient solution because the mechanical parts are placed out of the MSM's workspace, it may be one of best solutions for our special crane because two design assumptions are practically reasonable. However, this concept brings a negative effect on the transmission efficiency.

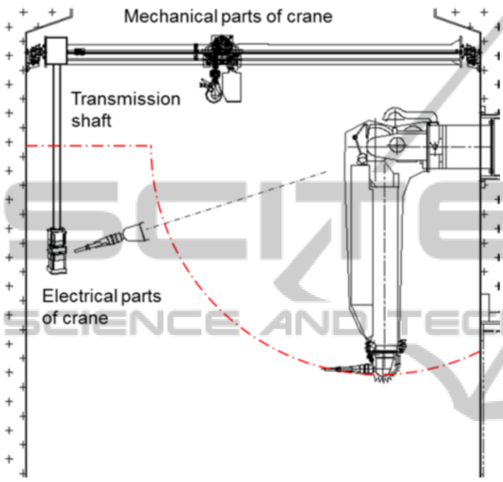

Figure 2: Concept of remote actuation mechanism for power transmission.

This mechanism resembles that of a tendon driven manipulator in which the torque generated by the motor installed on the base is transmitted through the tendon to the load links placed far from the base. This approach is advantageous in reducing the bulk and weight of the arm, and therefore similar effects may be expected in the crane system. For example, the space of the excluded electrical parts from the crane make it possible to reduce the height of the crane system with a slight sacrifice in width. In addition, because the power and signal cables can be placed in a lower position near the servo-motor, the volume of the cable carrier is not required in a higher position near the mechanical parts of the crane, which maximizes the working volume of the traveling motion of the crane.

3.2 Design of Mechanical Structure

Figure 3 shows the 3D CAD model of the prototype crane system with a remote actuation mechanism. As in an industrial bridge crane, it consists of three motion modules: a traveling system, traversing system, and hoist system. To provide accurate motion and absolute positioning, all three axes of the crane system have been designed to be equipped with an anti-slip driving structure. As for the traveling system, the overall weights of the crane and loads are supported by four wheels axially coupled with pinion gears. The gears mate with a rack gear mounted on the runway rail to prevent the system from slippage. The level of the wheels can be adjusted using a shim plate.

The traversing system moves a trolley hoist in the forward/backward direction from the viewpoint of the operator, and supporting frame and girder have been designed in consideration of the stress and deflection at the maximum payload condition. Because the traversing system is operated using a linear motion system such as an LM guide and ball screw unit, and its motion features anti-slip property with a small amount of friction.

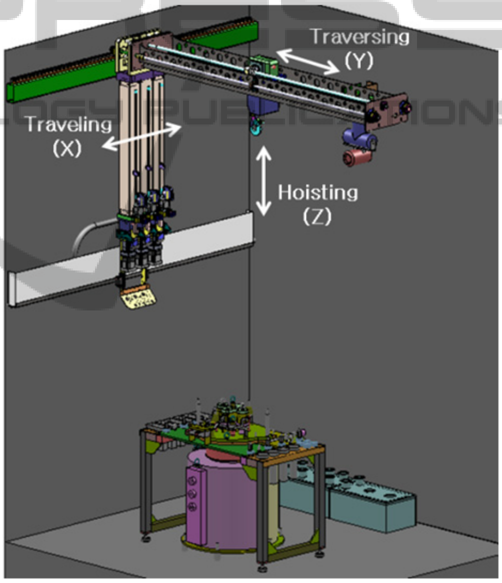

Figure 3: 3D CAD model of crane system.

The detailed design of the hoist is shown in Fig. 4. It consists of a worm gear, a chain wheel, and a ball spline. Two spline nuts were inserted in both sides of the worm. Since the spline mechanism is used to provide nearly frictionless linear motion while allowing the member to transmit torque simultaneously, the traversing motion of a ball screw cannot interfere with the hoist motion. As a good way to increase the durability of the mechanical parts of the crane, we used commercially proven components such as a ball-screw, ball-spline, and linear motion guide so as not to be broken within the expected lifetime of the crane system.

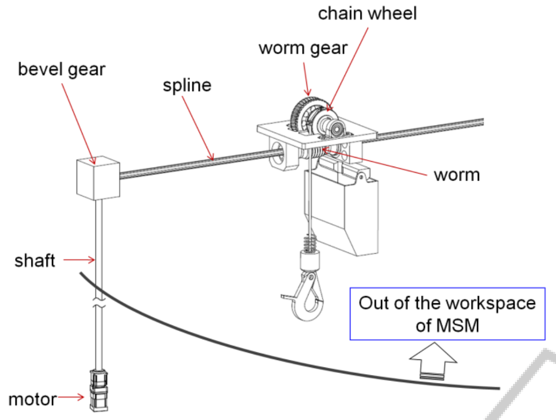

Figure 4: Novel hoisting concept employing remote actuation mechanism in which the driving power is transmitted from a remotely installed servo-motor.

3.3 Modular Design for Easy Maintenance

A remote handling module is a module that can be remotely operated (connected or disconnected) by a robot or manipulator and its design must include interfaces that are more easily handled with manipulators and special tools. Therefore, the easy maintenance concept is a major goal in the design of remote handling modules because it minimizes the shut-down times. The driving module should be firmly fixed to the frame while connecting the transmission shaft to the motor shaft, and it can also be easily separable from the frame in a remote manner. To do so, we applied a cam-slider mechanism as a locking device. In a sensor module consisting of a wire sensor and two limit switches, the ball-spring mechanism is used to ease the mechanical attachment/detachment (Fig. 5).

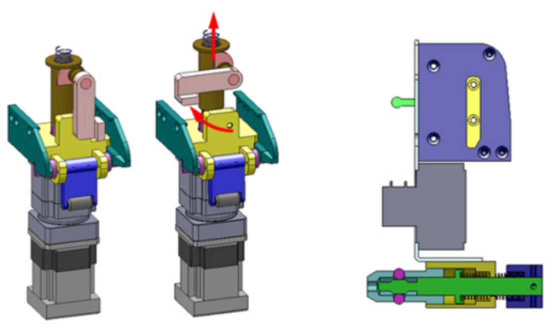

Figure 5: Easy maintenance concept of remote handling modules: a drive module (left) and a sensor module (right).

3.4 Hook

During crane operations, hooking is one of the most easy and simple operations if a human operator performs it. On the other hand, if it is performed by the master-slave operation using a robotic gripper, it is very difficult and complicated work to perform because it consists of three motions: safety latch release, gripping, and hooking. Furthermore, the work performed using one gripper may be much harder since the handling points of three motions are different from each other. As an improvement of the conventional hook shown in Fig 6 (a), a pistol grip is added to the hook and its gripping motion is interlocked with the opening of the latch. However, the eccentricity between the centre of the hook and the centre of the grip often causes an unstable grip. Furthermore, the initial approaching posture of the gripper to the pistol grip should be set appropriately at the beginning of the operation, which is occasionally difficult without a change in the location of the manipulator.

A novel hook, as shown in Fig. 6 (c), has been devised to provide a more efficient means for easy remote handling. A circular grip is concentrically coupled at the central line of the hook so that a gripper can approach the grip from any initial direction, and it can also grasp the hook firmly. As the gripper lifts the grip of the hook up, the safety latch rotates to be opened with the interaction of the guide slots and guide pins fixed on the safety latch. Therefore, the gripper should be required to perform two simple motions such as a grip and up/down movement at the same handling point, which dramatically simplifies the remote handling of the hook.

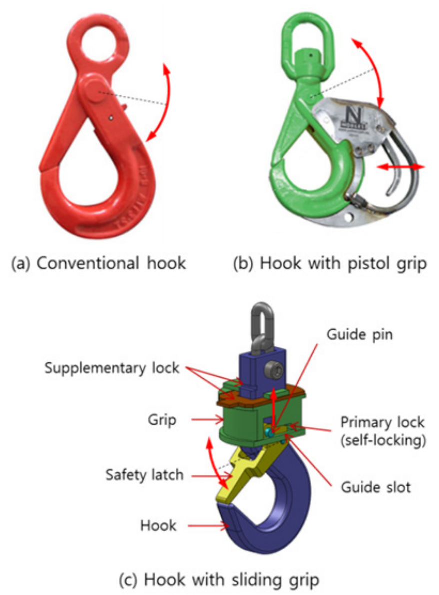

Figure 6: Conventional hook and its improvements.

4 CONTROL SYSTEM OF CRANE

Manual operation of a crane while watching inside the hot-cell through a lead-glass shielding window often fails in accomplishing the given tasks due to an imprecise operator cognition. In addition, because the location of the processing equipment is known to be a priori in an argon compartment, predefined sequential operations can simplify the complicated operation. Therefore, we designed a remote control system based on absolute positioning and automatic operation to provide a safer and more efficient operation of the processing equipment. The crane has 3 degrees of freedom actuated with Tamagawa brushless servo motors equipped with a resolver sensor. We designed a control system on the basis of the servo control. The absolute position of each motion axis can be measured using a wire sensor in which a multi-turn potentiometer is coupled with a steel wire.

To increase the performance of the absolute positioning measurement, we used a combination of a wire sensor and resolver pulse reading. When the control system is re-initialized, it reads the absolute position from the wire sensor through an analog-to-digital conversion, and set the value as the initial position of the crane system. Next, the motion control system uses resolver pulse readings instead of wire sensor readings because the resolver pulse is much more robust against noise. Since the analog readings from a wire sensor are normally affected by noise, the average value of the preset time duration is chosen as the initial value. In addition, whenever the limit switch is activated, the control system resets the origin as the preset value in absolute Cartesian coordinates. This makes it possible for the control system to be operated in absolute positioning mode.

Figure 7 shows the overall layout of the control system in which a digital signal processor (DSP)-based controller interfaces with both the camera controller and motion controller. Servo motors are operated in position control mode with various speed profiles. The DSP controller receives control parameters from the PC through network communication, and transfers operational information to the PC. The operator can manipulate the crane system by looking through the lead-glass shielding window and viewing a supplementary camera monitor. All functions concerning the control of the crane and camera are interfaced with a touch pendant through RS-485 communication.

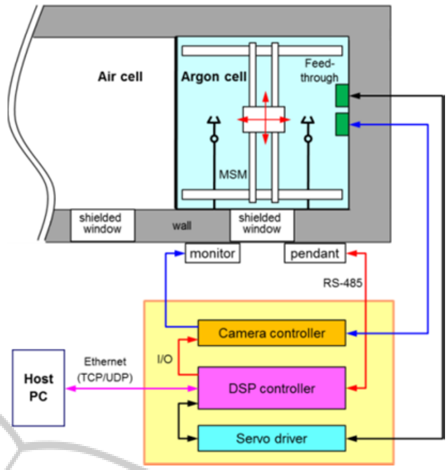

Figure 7: Overall layout of the integrated control system.

5 PROTOTYPE OF CRANE SYSTEM

Figure 8 shows a full-scale evaluation mock-up facility that provides same operation conditions and useful means for testing and verifying the remote operability and maintainability of the constructed process equipment, cell utilities, and relevant devices in advance before they are installed in the argon compartment of the ACPF. Cell utilities consisting of a window, a cell light, an antechamber for transportation, a door, two sets of MSMs, a feed-through, and a camera system were installed inside the argon compartment, while a camera monitor and touch pendant for crane control were installed around the window in the operation area. Several mechanical and electrical tests were performed to check whether the crane system is performing to the desired level of performance. The maximum deflection of the girder frame is about 0.3 mm, which may not influence the performance of the linear motion system, such as the ball screw and ball spline. Because the mechanical parts of the crane system were placed over the MSM, the load hook can be moved along the ceiling without any interference with the MSMs. Several control modes such as jog mode, absolute positioning mode, and sequential operation mode can be selectively performed using a touch pendant in which several graphic pages linked to each control mode.

As shown in Fig. 9, several remote maintenance operations have been performed to verify that the driving modules and sensor modules can be replaced using an MSM only. From the experimental results, all the design goals have been generally achieved, especially in the concept of remote maintainability.

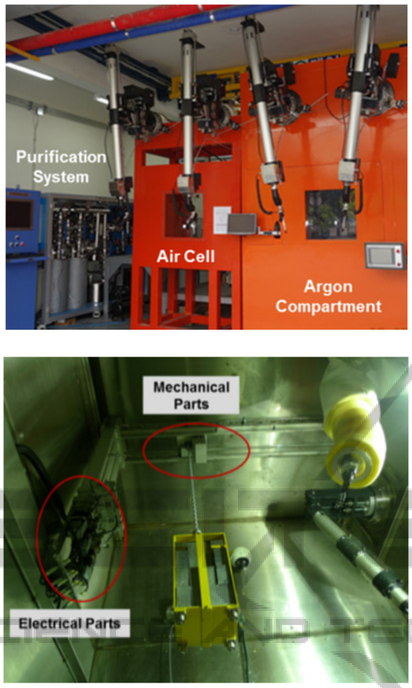

Figure 8: Operation area (top) and inside of argon compartment (bottom) of the constructed mock-up facility.

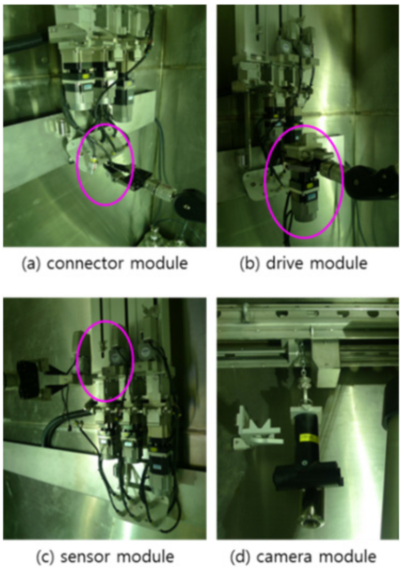

Figure 9: Evaluation test of remote maintenance.

6 CONCLUSIONS

In this work, we developed a crane system for use in a small argon compartment which has several constraints on the facility, remote handling device, and process operation. To increase the remote maintainability of the crane system, we devised a novel crane system in which its mechanical part and electrical parts are separated and connected through a transmission shaft. In this concept, the electrical parts, which have more possibilities of a breakdown than mechanical ones, can be remotely replaceable while the mechanical parts are designed to have a high safety margin so as not to be broken within the expected lifetime of the crane system. In addition, all hardware and software of the DSP motion control system based on absolute positioning technology were developed and implemented for the control of the crane system; therefore, it is possible for us to perform the given tasks more safely through automatic operation. From several operation and maintenance tests of the constructed prototype crane system, all design goals have been generally achieved, especially in the concept of remote maintainability. We are now applying an anti-sway control technique to provide a more accurate and safer operation of the process equipment.

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