Suspendable Servo Manipulator for Hot Cell Application

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Abstract

The paper discusses the design considerations, development, mission trials and deployment of a tele-manipulator arm for removal of radioactive vitrified waste in hotcells. Due to their limited reach, conventional manipulators installed in the cell cannot be used for the mission. The customized arm was designed specific to the site operational requirements such as easy installation in cell with minimal human intervention, short term deployment, flexible reach and survival of equipment for the operation lifecycle. The design parameters are optimized to achieve the above mentioned objectives using commercially available components.

Introduction

In processing plants, high temperature process melters are used to vitrify radioactive waste in glass medium. Molten vitrified mass from melters is poured into stainless steel canisters for storage and their subsequent disposal at geological disposal facilities. At the end of each pouring cycle, some molten waste solidifies as a rigid glass thread. These threads, which are formed at the outlet of the furnace, break during canister handling and fall on a circular turntable below the furnace. The manipulators installed for long term use in the cell are usually employed to pick up the threads. However, a few glass pieces remain inaccessible due to limited reach of the manipulators. Over a period of time, vitrified waste pieces accumulated on the turn table resulting in very high levels of radiation dose inside the cell. Removal of glass threads was essential to allow personnel access to cell for undertaking maintenance and associated activities relating to plant operation.

A customized electromechanical tele-manipulator arm was developed for the activity reduction campaign to handle and dispose the waste. Essential design inputs for the equipment were obtained through initial site survey and interaction with plant personnel. A video survey of the operating area provided the basic design inputs such as: approximate number of threads to be picked (around 50), sizes of glass threads (5-30 cm in length and 5-50 mm in diameter), and their distribution pattern. The glass pieces were brittle and weighed up to few tens of grams.

A rough estimate of radiation dose rates in the operating area was obtained from previously measured site readings, analytical methods of dose rates evaluation and relevant statistical data.

Mechanical Design Considerations

Arm configuration

Due to large number of active vitrified waste pieces accumulated below the melters, there was high radiation dose in the cell. As personnel entry was restricted, it was not possible to install a remote handling gadget in the cell. The cell has a highly unstructured environment with limited free space. Moreover, the waste pieces were distributed over a wide area. These constraints imposed severe limitations on capability of conventional remote handling systems to access all target locations. A novel design concept was therefore formulated to overcome these issues.

Fig 1: Vitrified waste pieces in cell

As the cell is equipped with an overhead crane, it was envisaged to develop a customized slave manipulator arm which can be suspended from the crane hook during operation. It would be easier to introduce such an arm in the cell and would also provide necessary reach for the operation as the arm could be dynamically transported to the area of interest. Vertical motion of crane load hook would allow coarse vertical movement of the manipulator. Using a combination of arm joint motions, fine adjustment required for correct positioning of the gripper could be achieved. As per site layout constraints and target locations, a five axis articulated arm consisting of one base rotation, two arm swivels, two wrist motions, and a grip motion was found adequate to accomplish the task. The ranges of base and arm motions were limited to ± 180° and ± 90° respectively.

A small master arm was developed to remotely control the slave arm. It was placed in control centre as shown in figure 6. The two arms were electrically connected using a long sheathed cable. Slave was operated using video feed provided by the cameras installed in cell and manipulator.

As the slave arm is suspended, any abrupt change in manipulator joint configuration could cause oscillation of the arm. One of the precautionary design aspect incorporated to minimise the oscillations is meticulous balancing of the joints. Shoulder joint and elbow joint were designed with appropriate counter weights such that joints are perfectly balanced. This arrangement has also reduced torque demand at the joints. Vibrations due to small actuations of the arm joints were effectively minimized through inertial damping provided by the non moving base of slave arm. The base fitted with electronic control elements of the equipment and its lead shielding weighed double the remaining arm of the manipulator. The shape and configuration of the gripper was decided based on diameter of the smallest glass piece to be picked up, nature of the surface upon which the objects are lying and the surface finish of the object. Extensive trials were conducted using grippers having parallel and angular jaws (figure 5) to pick a variety of objects. Based on the results obtained from the trials, it was concluded that a parallel jaw gripper with long fingers would be most suitable for the operation.

Fig. 2: Suspended Slave arm

The gripper must apply minimal gripping force to pick delicate glass objects. Also it should be able to firmly grip electrical cables, which are attached to the arm and may obstruct its free movement during operation. To meet these requirements, a control scheme was designed to provide different gripping forces to the end effecter as per requirement.

The electrical/electronic components in the arm require shielding from radiation to reliably operate for the service duration. Based on the available data for cell dose rate and component life under radiation, shielding schemes were implemented for various components like electric motors, encoders, drives and controller.

Torque estimation

The heavy manipulator suspended from the overhead crane behaves like a huge pendulus mass. Any swift rotation of joints may cause oscillations in the suspended robot arm. Therefore fast movement of joints are restricted in the design. The design torque selected for each joint is the maximum torque experienced in fully extended configuration under rated load. The torque required to overcome frictional load is also considered in the computation. Acceleration torques for joint rotations are excluded as the operating speeds are low.

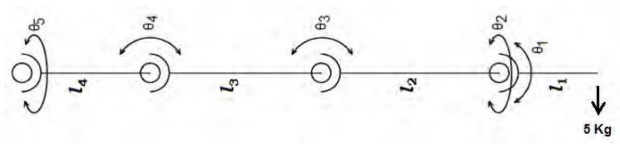

Fig 3. Joints and links of manipulator

Let ‘T_i’ be the torque required at the i^{th} joint of the arm, (i=1,2,3,4,5). If ‘P’ denotes the payload of the arm, then:

$T_1 = (l_1) \times P + T_{1f}$

$T_2 = T_{2f}$

$T_3 = (l_1 + l_2) \times P + T_{3f}$

$T_4 = (l_1 + l_2 + l_3) \times P + T_{4f}$

$T_5 = T_{5f}$

Where T_{5f}, T_{4f}, T_{3f}, T_{2f}, T_{1f} are friction torque values of the joints. Joint θ_5 experiences the weight of the manipulator in the axial direction. Therefore torque required to overcome friction alone is considered at

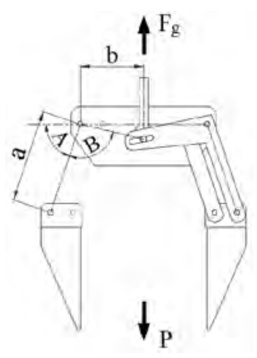

Fig 4. Gripper links and forces

θ_5. Apart from these joints, there is a gripper at the end of the link l_1. It is operated by applying an axial pull as shown in figure 4. The axial force F_g required to grip a payload P is given by:

$F_g = P\ a\ \mathrm{cosec}(A + \theta) / \mu\ b$;

where, μ = coefficient of static friction between gripper jaw and work piece.

Electrical Design Considerations

Movement of manipulator over large area was unavoidable in this mission. So a mobile manipulator has been envisaged to cover the workspace. Considering the difficulties of cable management, it was decided to keep provision for complete cordless operation of the system. This influenced the selection of electric supply for slave side as 48 volt DC. However anticipating regulatory restrictions on the usage of storage cells in radioactive area, the choice of cordless mode of operation was discarded. Instead it was decided to use an umbilical cable to feed power and control separately to the slave arm.

Speed and torque required at every joint of the manipulator was computed based on which, Brushless DC motors, drives and multi-axis motion controller were selected from vender's catalogue. Brushed DC motor was an alternate economical choice for the selection; however immediate availability of appropriate size favoured selection of Brushless DC motors.

Knowledge of radiation levels a component might survive is an important input for designing layout and general arrangement for control components. In this respect, an analysis of radiation survival limit of control components has been examined. Most of the commercial silicon based electronics survive radiation levels in the range of 500 - 1000 rads. Electrical motors with passive feedback sensors also survive 30 - 40 Kilo rads.

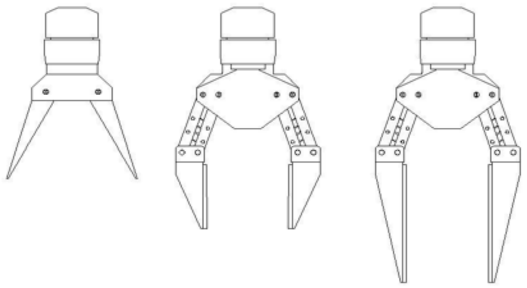

Fig 5. (a) Angular jaw gripper ; (b&c) Parallel jaw grippers

Components on the arm get radiation exposure in relation to their distance from the source. The layout of critical components was decided according to their safe level of

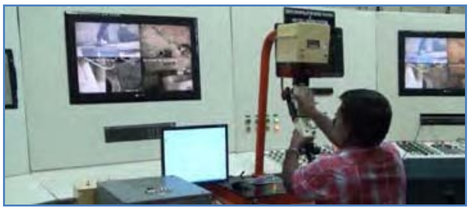

Fig.6: Master arm operated at the control

tolerance. The gripper located closest to the radiation source receives highest exposure. The electrical components such as motors and sensors, which control the gripper operation, were mounted at a distance of one meter from the gripper near the elbow joint. The mounting distance is adequate for electric motors to survive the mission as they have a higher radiation tolerance. A thick metallic shield was fitted to protect the feedback elements, which are more vulnerable to radiation damage, located at the rear end of the motors.

In general, commercial grade control components are vulnerable to radiation damage if total exposure of the component exceeds 400 rads. All such electronic elements were mounted in a shielded zone at the base of the manipulator. This zone was located around two metres away from the radiation source in most of the circumstances. The zone was shielded with thick lead bricks to bring down the radiation level below 400 rads during the mission. As the size of the shielded zone must be minimised, a compact multi-axis sandwiched type drive and controller were chosen for control.

The slave manipulator arm has six motors and each of these motors have power, feedback and brake cables. Considering the difficulty of handling several multi core cables over a long distance, it was decided to install the controller and drive on the slave arm. The choice of multi-axis sandwiched type multiple drives helped in reducing the trouble of cable handling as this scheme demands only

Fig. 7: Image of slave arm in operation

an umbilical cord for power and an Ethernet cable for communication.

The requirement for the system was urgent and lead time for design and development was barely adequate to undertake a detailed analysis. The design philosophy of single mission based equipment, simplistic design approach, and use of standard bought out parts, was adopted to reduce development time.

There are several in-cell cameras installed in the plant which provided video images of slave arm in operation as shown in figure 7. To enhance visual feedback, two more cameras with pan, tilt and zoom facilities have been mounted on the manipulator. Real time views from these cameras were displayed to the operator for close look of the object. Towards the end of the mission one camera, which was installed near the gripper, lost its functionality.

Field Trials and Deployment

Prior to cell deployment, field trials were conducted to ensure the worthiness of the system in the cell. The slave manipulator was suspended from an overhead crane in site as shown in figure 2. The system repeatedly operated for a period exceeding expected mission duration to test the reliability of operation and to train the operators to operate the system. Extensive trials were carried out on picking of inactive glass threads of similar dimensions to evaluate the efficacy of gripping without damaging the fragile glass objects. Picking of small diameter glass threads was tried with angular jaw gripper and parallel jaw gripper and 100 mm wide parallel jaw gripper was found more acceptable for the operation.

Conclusion

Suspendable servo manipulator is a novel design which uses transporter to access a much larger work space in comparison to conventional systems. The system was built in a short duration using commercial grade components. The following key concepts were utilised in the development of the equipment for short term application in highly radioactive area.

a) Every component has a finite survival time in radiation field. Hence in principle all such devices are useful in radiation fields for limited duration.

b) Some part of the equipment is less exposed to radiation than the other. Component layout may be designed such that critical and sensitive components have reduced exposure to radiation fields.

c) Without sacrificing the core functionality of the remote handling equipment, shielded zones can be created which would enhance the life of critical and vulnerable components.

d) Use of compact and efficient components reduce heat dissipation and hence enable to have compact shielded zones.

Extensive trials were conducted to make the system worthy for deployment. These trials were instrumental in reducing the actual duration of the mission as the operators gained experience.

Acknowledgment

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