Telerobotics Requirements for Remote Handling in Nuclear Facilities – 17538

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ABSTRACT

The main constraint in scientific nuclear facilities is the environmental conditions inside the operational areas which imply restrictive equipment requirements to resist high radiation levels and other restrictions related to magnetism, ultra-vacuum, and/or temperature. Robots for remote handling systems are required to perform inspection and maintenance operations since direct human intervention is not allowed, or constrained, under these environmental conditions. Several challenges have to be solved in teleoperation technologies in order to properly perform remote tasks in scientific nuclear radiation facilities. The main solutions described in this paper are based on using multiplexer for the transmission of signals and applying hybrid rate/position control algorithm so as to improve telemanipulation in these environments. Both developments have been evaluated and discussed.

INTRODUCTION

There are several worldwide nuclear scientific facilities that are focused on the development of research studies under irradiated environments. This paper emphasizes the facilities focused on nuclear energy to generate elecricity by nuclear fusion, being cited: JET (Joint European Torus) [13], ITER (International Thermonuclear Experimental Reactor) [13], IFMIF (International Fusion Materials Irradiation Facility) [13] y DONES (DEMO-Oriented Neutron Source) [2]. These facilities and others installations must operate under certain levels of radiation to culminate the work for which they have been designed.

Radiation and other factors cause greater physical-chemical deterioration in the materials located in this environment. For such reason, appropriate materials and components (RadHard) must be selected for this type of conditions [13], in order to shield the operating room and to protect electronic devices that are exposed to radiation. However, to ensure greater reliability and availability, it is also necessary to perform scheduled maintenance scheduled stops at every certain period of activity [2]. Performing whenever possible, remote handling operations by robots to access critical areas of the facility [10,11]. Thus, remote handling operation avoids human exposure in these hazardous environments and the corresponding long waits until the doses of radiation are tolerated by humans. Telemanipulation provides great advantages for inspection, maintenance and waste management. Nevertheless , telemanipulation work is a challenge due to: radiation, dimensions, precision and heavy loads among others. These should be addressed for the proper operation of the system. So, throughout this paper, a series of techniques that allow attenuating the problems that originate in installations with an irradiated environment are pointed out.

On the other hand, telemanipulation systems are commonly used for a fairly narrow variety of manipulation tasks to inspection, maintenance and waste management. However, there is a lack of tests and metrics within the telemanipulation literature, since most of the studies are focused on a few selected tasks that do not cover the full operational range of required remote handling tasks [4]. This causes a lack of knowledge for engineers and readers interested in this field.

TELEOPERATION CHALLENGES IN RADIATION ENVIRONMENTS

Due to the high levels of radiation after the period of operation in the active areas, robots are appropriated for performing remote tasks. Wherein the operator has to perform remote tasks, the remote equipment such as cranes, servo-manipulators or grippers are located in the active area. These are equipments are teleoperated remotely through the corresponding operator interface in a control room; which is a completely safe room without risk to the operator.

The proper execution of telemanipulation tasks in scientific facilities with radiation are a technological challenge. For this reason, several investigations attempt to solve the problems caused by the environmental and working conditions of this type of installations [6,8,12].

Main Requirements for Remote Handling Equipments

Execution of remote handling task in scientific nuclear facilities, such as those previously mentioned [5,7,13,14], requires a high degree of immersion of the operator in the remote robot working place. It implies that operator has to perceive robot movements as an extension of his/her hands and also receive information about the force interaction between remote robot and its environment. For this reason, haptic master devices are use by operators to properly command robots [16]. Two of the main requirements to properly design a remote handling system for scientific nuclear facilities are as follows:

• **Radiation tolerance**: radiation from the facilities is harmful to the environment where it is contained. Since the components degrade more quickly, communication signals are affected, electronics deteriorate and human exposure at certain levels is dangerous and unviable. This justifies using telerobotics and devices that are remotely manipulatd in such environments.

• **Large work space dimensions**: operator use a master device to remotely guide a robot [2]. Usually, there are significant differences between the master device and the robot workplace. Therefore, adapting operator and robot workspace by using a specific technique that properly matches dimensions of both workspaces have to be applied.

• High level of **operator immersion** in the robot working space: execution task performance strongly depends of the operator dexterity and it is directly related to the operator perception of the remote robot environment, which it is also defined as operator immersion. This factor is crucial in order to reduce the execution time of remote task and it directly correlate to the system performance and productivity.

• **Handling of heavy loads**: Force feedback devices usually apply a scale factor to reflect forces. This technique is not able to be done in case of remotely manipulating heavy loads since scale factor has to be too high. In this case, it is more appropriate to apply techniques based on events that improve the operator perception in case of contact.

Most relevant factors have been introduced above. The two following sections are focused on describing solutions related to radiation tolerance and guidance of robots in large workspaces.

MULTIPLEXOR OF ROBOT CONTROLER SIGNALS

The use of a multiplexor close to the base of a robot is a solution to avoid the radiation effects on the robot controller, since it is required to properly shield robot controller to protect it from the bombardment of neutrons and particles. Another possibility is the offshoring of the robot controller in a place free of radiation, but it requires using a high number of wiring and potential noises in the signals. A signal multiplexor can solve partially this problem since number of signal is strongly reduced. However, multiplexors are based on electronic circuits and RadHard components have to be used.

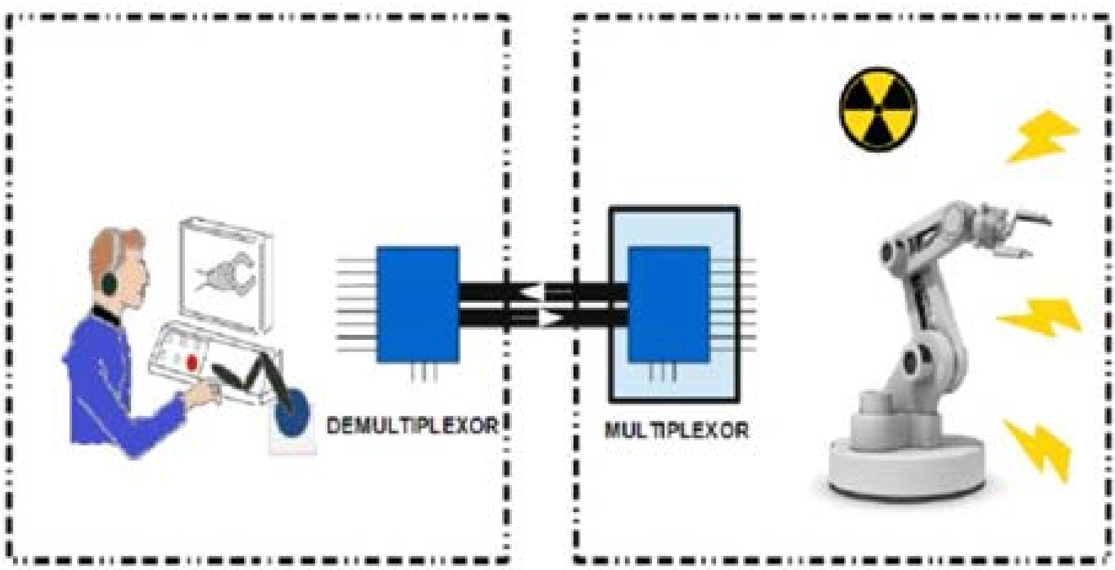


Fig. 1. Basic diagram of the communication with multiplexed signal.

A diagram of a multiplexor/demultiplexor architecture is shown in Fig. 1. Signals are digitalized and multiplexed close to robot base and transmit to the control room by using a single cable, reverse operation is done by a demultiplexor in the control room in order to reconstruct the original signals. This solution could solve problems related to shielding electronic equipment, signal noise and wiring volume. A theoretical study on the feasibility of the development of multiplexing electronics should be carried out under extreme conditions of radiation such as in the maintenance operations of the ITER or DONES installations.

Discussion of multiplexer solution

The proper connection between the remote equipment and the control room is crucial for the accomplishment of the tasks. Thereby, the reliability of the connection with all the instrumentation is a vital requirement. Usually, a large volume of wiring to encompass all sensors and actuators of the various devices located in the remote environment is required for communications. This is a disadvantage when there are harsh conditions, because the cables deteriorate more frequently and should be replaced periodically. In this way, if the number of cables is high, it will increase the cost to invest, the time and the difficulty in carrying out the maintenance task.

The main idea of multiplexing technology is based on encoding many signals through a multiplexer and extracting a single cable shared channel in the radiated environment. Subsequently, when the cable is in a safe zone of radiation, a demultiplexer decodes the signal and it obtains all those signals compressed, which corresponds to the data sent by the sensors and actuators of the robot. This allows reducing the section and weight of the amount of wiring, since several signals share a single conductor, such as a copper wire or fiber optic cable.

Three considerations must be taken for the correct functioning and useful life of the electronics of the multiplexer in the irradiated zone:

- RadHard device highly tested and qualified for the life of the multiplexer.
- Shielding of electronics with materials that shield gamma rays such as lead (Pb) or tungsten (W).
- Cooling to avoid high temperatures affecting electronics if required.

There is not any commercial multiplexor in the market currently that meets nuclear fusion requirements (10kGy/h gamma dose). Therefore, a specific multiplexor based on RadHard customized ASIC is proposed. This option is provided by several companies such as MAGyICs and Aeroflex. This is very expensive solution that implies an initial investment around 0,5 – 1,0 Million dollars. However, more applications such as military and aerospace can benefit from this technology. If requirements from several application can be comply then a new generation of multiplexor based on RadHard ASIC can be developed, as result more robust and simple communications system could be used for telerobotics applications.

MATCHING WORKING SPACES BY USING A "RATE – POSITION” ALGORITHM

Two control modes are usually applied for guiding a robot in large workspaces, these control modes are: rate (or speed) control and indexing control [2, 15]. A first approach to match robot and master workspaces is to implement a rate control in the master. It implies that master generates a robot rate command (velocity and direction) when the master is displaced from the equilibrium position. This method is adequate for long displacements but motion precision is poor.

Another solution is to apply an indexing control mode by using a on-off position-position control between master and robot. It implies that master guides the robot (on) until is achieved master’s workspace limit, in this case master device is decoupling (off) to the robot in order to resincronize both devices. Indexing method generates disorientation due to changes in the position reference.

A new and more intuitive method is proposed called “rate-position control” [1] has been developed iIn order to combine benefits from both methods. This method allows changing control mode more naturally and helps to solve workspace differences for telemanipulation. The control rate-position method is based on dividing master’s workspace into two spherical areas as shown in Fig. 2, where the different states are defined.

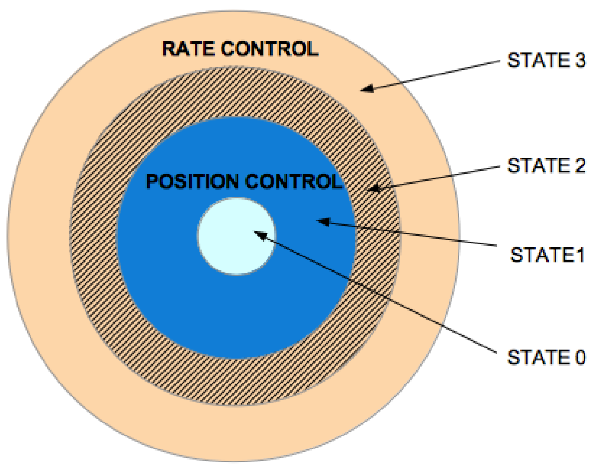


Fig 2. Area of the rate-position controller.

• State 0 "go to the center":This state is the home location that places the master device in a central position (state 0) in the following cases: when system is starting-up, or when switching from rate control to position control. The objective of this state is to locate the central point of reference and synchronize it with the current position of the robot.

• Status 1 "control in position":The operator controls the slave robot in position and receives the forces of interaction with the environment. The slave imitates the movements executed by the master (operator) as long as the device is within the dimensions of the circumference of the position control.

• State 2 "vibratory phase":This state occurs when the operator exceeds the spherical zone of the position control. A vibratory stimulus indicates to the user that he has surpassed the working space position and there is a transition to control in speed.

• Status 3 "rate control": This mode allows teleoperation with rate commands. In addition, the operator feels a force proportional to the distance towards the centre for safety. So, if the operator moves away from the sphere will feel a greater force.

Evaluation of rate-Position control mode

Some experiments have been developed in order to evaluate the performance of the proposed control algorithm. For this evaluation, it has been proposed the execution of a telemanipulation experiment that implements the different control modes for the same task.

In the validation of the rate-position, an experiment has been proposed that compares this method with respect to the previously discussed indexing method and the control in position performed with a kinematic master similar to that of the slave.

A robotic hydraulic arm of 6 degrees of freedom from Kraft Telerobotics with a robotic hand of 3 fingers robot hand from Robotiq have been used as slave robot. As master device have been used the following devices: three fingers haptic device developed by the UPM [8] which is controlled by two control modes (indexing and rate-position), and the master interface provided by Krafat Telerobotics which is controlled in position-position control mode. The result of the combination of all the devices can be seen in Fig. 3.

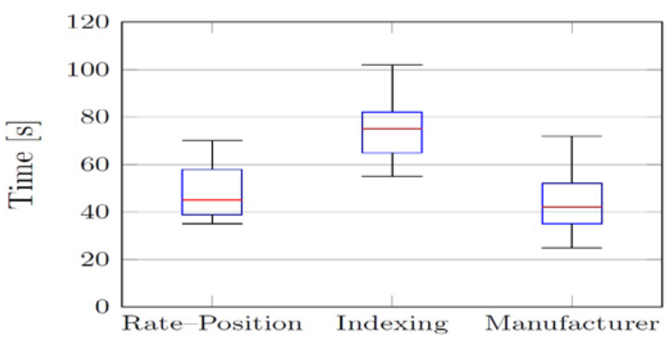
Fig. 3. Operator performing a complex telemanipulation task.

These three methods are compared by the execution of the same task: the telemanipulation of a fragile object (a bulb). The steps of the task are:

1. The task begins with the robot in a designated position, located one meter away from the target;
2. The user has to approximate to the manipulation area where the light bulb is located on top of a glass and position the robot in the pre-grasp pose;
3. The user will command the robotic hand to grasp the light bulb;
4. The user will command the robot back to the starting position without breaking or releasing the light bulb;
5. The user will move back to the manipulation area (still holding the light bulb) where the fragile object was located and position the robot in a pre-release pose.
6. The user will command the robotic hand to place the light bulb at its starting position.

The experiment was performed 30 times by two subjects with each of the three methods. The task processed by the subjects consisted of carrying out actions of remote manipulation with a robot and its delicate robotic hand. For safety reasons, the experiments were carried out with people from the telerobotic group of the UPM. These users had prior experience with the 3-Finger haptic device and the manufacturer's drivers. However, they were not familiar with indexing techniques or the rate-position controller.

Execution time for task completion
As show in Fig. 4, the execution time to perform the fragile dexterous manipulation task, for the rate-position controller is in average, 68.9 seconds; while for the indexing control, the average time spent to perform the task is 75.33 seconds. Using the kinematically-similar master with the robotic hand controllers, the time goes in average to 70.67 seconds.



ANOVA Table

Source	SS	df	MS	F	p-value
Columns	17401	2	8700.51	52.64	1.04×10^{-15}
Error	14378.6	87	165.27		
Total	31779.6	89			

Fig. 4. ANOVA: Comparison of times when performing a skillful manipulation task with different control methods.

It can be seen that the indexing method has a higher average time to complete the task than any of the others. Moreover, subjects were more tired after finishing the trials with the indexing method than the others. The very small p-value indicates that differences between column means are highly significant. Reason is they had to move their arm forward and backward continuously and press a button when covering large distances.

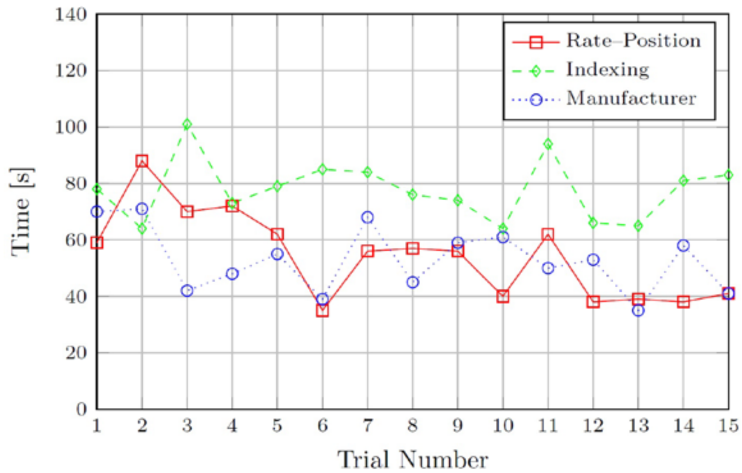


Fig. 5. Training time when performing a skillful manipulation task with different control methods.

The rate-position method is similar in time to those obtained by using a kinematically similar master and some sliders by two people, which is intuitive since one person is only focused in the control of the hand, while the other subject is in charge of moving the robotic arm with a scale 1:1.

Fig. 5 shows that the training time for the rate-position control drops from 70 to 45 seconds after five trials; the indexing mode it remains constant at about 80 seconds, and it does not reduces during the 15 trials; for the manufacturer controller, the time lowers from 65 to 45 seconds after the 3rd trial. This shows that five trials are enough to get used to the rate-position control method to perform a dexterous task; which is admissible. Since subjects are usually trained to use computer interface with an indexing control mode, such as a computer mouse; it seemed very intuitive for them to move the robot around with this control. However, the longer time is due to the fact that they had to move more distance in the slave device than in the master device and they needed to keep a button pressed in order to decouple both systems.

Task success rate

Moreover, Fig.6 shows that while the rate-position and indexing controllers have achieved a 100% success rate; for the manufacturer controllers, this percentage drops to 93.33%. After questioning the subjects, they mentioned that the main difficulty when using the manufacturer controller was the coordination between fingers when closing the hand with the sliders and keeping the robotic arm still while doing this. 93.33% may seem a high success rate, but for some situations that involve risk such as bomb dismantling, telesurgery or maintenance of nuclear reactor, a drop of 6.67 points in the percentage may not be admissible, this failures could be explained because users have force-feedback and feel the grasping, despite the sliders don't provide this information and the operator has to ensure a proper grasping visually.

Fig. 6. Successful manipulations when performing a dexterous manipulation task with different control methods.

CONCLUSION

Maintenance and other operations such as handling of waste, repairs or manipulation of components by means of a telemanipulation equipment are more complex in irradiated environments or under extreme conditions. This causes more deterioration of the components, problems with communications, delays, noise, instability, danger, etc. Proposed solutions have been based on solving the problems caused by radiation with multiplexor/demultiplexor systems based on RadHard ASIC to transmit signals, and the use of a new control algorithm "rate-position controller". These methods have been evaluated with good results in order to improve teleoperation tasks in scientific nuclear facilities.

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