BRAZILIAN JOURNAL
OF
RADIATION SCIENCES
08-03A (2020) 01-15

Anatomical movement replicator applied to activities in ionizing radiation fields

D` Martins[a] E., Mesquita[a] A.Z, Almeida[a] V.F, Palma[b] D.A.P., and Viana[c] W.

[a]Centro de Desenvolvimento da Tecnologia Nuclear (CDTN)/ Núcleo de Irradiação Gama (Nuclig), Postal code: 31270-901, Belo Horizonte, MG, Brazil

[b]Comissão Nacional de Energia Nuclear (Cnen)/Serviço de Análise de Segurança (Sease)/ Postal code 22.290-901, Rio de Janeiro, RJ, Brazil

[c]Centro Universitário do Sul de Minas (Unis/MG)/Unidade de Gestão de Engenharia, Arquitetura e Tecnologia (GEAT), Postal code 37.410-000, Varginha, MG, Brazil

amir@cdtn.br

ABSTRACT

The aim of this work is to demonstrate the need to develop more efficient means for radiological protection, making use of the latest automation and robotics technologies. A manipulator model has been developed that has technological differentials that can positively influence the performance and cost of remote manipulation. The built-in equipment has a Slave manipulator, developed without using semiconductor elements. They are housed in the control center, which is attached to the manipulator via umbilical cord, facilitating the equipment adaptation in hot cells and other working environments. The arrangement of the joints and the links, have similarities with the anatomy of the human arm, improving the instinctively of the operation. To demonstrate its technological feasibility, a prototype Master-Slave manipulator was designed, and built using three control programs, which were written exclusively for this work. It was also designed to reduce construction and operation costs, making it accessible to most areas. The results obtained with the prototype construction are shown to be promising, providing an incentive to continue the development of manipulators using similar technologies. The equipment, obtained satisfactory results in relation to the operability, being able to perform movement tasks of loads, as foreseen in the project.

Keywords: **ionizing radiation, radiological protection, robotics, automation.**

ISSN: 2319-0612
Accepted: 2020-07-16

1. INTRODUCTION

In the last decades, important advances have been achieved in the technologies of automation and robotics. These innovations were driven especially by the computation evolution, as much in the processing as in programming. As a result, there is a growing number of activities carried out by apparatus equipped with these technologies, whether in the industry with the manipulator arms and autonomous cargo carriers, or in automobiles that are made safer through the use of these technological advances.

One area that has played an important role in the development of these technologies is ionizing radiation. Since man has been trying to unlock the secrets of matter, systems have been developed to lessen the exposure of workers and researchers to the harmful ionizing radiations influence. For this purpose, manipulators and other mechanical, electronic and automated devices are used. However, these devices have characteristics that limit their use only to places where the radiation level is moderate, or to quite structured tasks.

In situations with very high radiation levels, it is difficult to maintain safe or viable operating distances between the operator and the radiation source when using mechanical manipulators. When manipulators are applied with digital electronic controls, they are negatively affected by radiation, causing permanent malfunction or damage to components [1], [2], [3].

Some of these devices can be replaced by analogue devices, such as potentiometers. The analog nature of these devices may carriage challenges to their use. However, it may offer some advantages such as greater robustness in relation to ionizing radiations and lower cost [4], [5], [6]. Through a construction with greater anatomical identity, it is intended to make the equipment operation more intuitive.

The purpose of this work is to develop an anatomical movement replicator applied to activities in ionizing radiation fields. It should be able to operate subject to fields higher than that tolerated by conventional servo-controlled manipulators [7]. The developed equipment will be useful in handling spent fuel elements, radioactive sources, and work in places subject to ionizing radiation.

2. MATERIALS AND METHODS

The following steps were used in the prototype development:

- Deficiencies analysis of the currently used systems.
- Analysis of the demands with the potential to be met by this technology.
- Development of 3D model and mechanical drawings of prototype, with four degrees of freedom. Possessing similarity to the joints of human arm, plus a clamp type forceps.
- Development of electronics control.
- Software development with implementation of Proportional–Integral–Derivative Controller - PID, statistical error control, fault detection, and motors command through Pulse-Width Modulation - PWM. It should be able to replicate the positioning of the master arm, controlled by the operator in the Slave device [8], [9], [10].
- Prototype assembly.
- Tests of equipment operation, without submission to ionizing radiation, to verify the motive capacity of the equipment and the facility of operation.

2.1. Boundary Conditions

The following requirements were adopted in the design of the equipment [7]:

- Control through replication of operator movements, improving command transfer. This parameter includes the improvement in the anatomical similarity of the equipment with the human arm.
- Development of servo motor model, with improved characteristics of resistance to ionizing radiation and with lower cost than the similar ones of the market.
- Experimentation of the concepts through the construction of prototype of Manipulator Arm Replicator of Movements.

  The equipment utilizes strategy of components protection differentiated from most equipment. This development is taking place in areas where other similar devices still present difficulties.

2.2. Mobility

To limit costs and labor expenditures, only four of the seven movements performed by the human arm were selected with the addition of a clamp type forceps. The joints were arranged so as to facilitate their use.

Shoulder rotation

This movement is described by the arm rotation through an axis that passes from shoulder to shoulder, latitudinal to the human body. This movement has an amplitude of 180 °.

Withdrawal and approximation

Movement described by the arm withdrawal and approximation of the operator body. It is performed by the shoulder movement and has an amplitude of 180 °.

Elbow flexion

This action is described by elbow flexion and extension. This movement has an amplitude of 150°.

Pulse rotation

Movement described by the effector rotation on the forearm axis. This movement has an amplitude of 170º.

Clamp

This movement performed by a clamp type forceps. It is described by opening and closing the forceps. This movement has an amplitude of 98 mm for the purpose of handling objects that have this maximum dimension.

2.3. Dimensions and Load Capacity

Dimensions

The dimensions of the "arm" and "forearm" at the elbows are 260 mm and 300 mm, respectively. These measurements were based on the average of the dimensions of the upper limbs of the authors. Thus, the activities carried out by the equipment will be close to that carried out by the arms of a man.

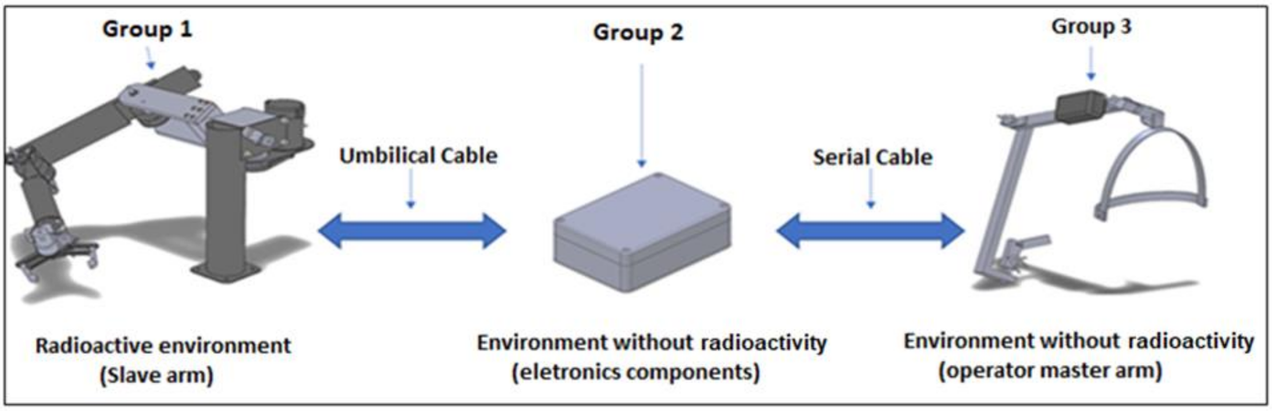
Load Capacity

This was defined based on the load capacity of the MA-30 model manufactured by the Swedish company La Calhène [11]. The maximum load this model is 25 to 35 newton (N). For the purpose of overcoming the technical MA-30 specifications a reference load of 50 N was set. The manipulator must be able to lift this load anywhere in the volume region representing the equipment work area. The position of the most unfavorable position must be considered in the project.

2.4. System setup

This Master-Slave manipulator system is designed to protect all sensitive parts from ionizing radiation. The system assembly was performed by distributing the components into three groups classified according to the need for radiological protection, as shown in Fig. 1. These groups are connected by different cables.

Figure 1: *Distribution of groups according to the need for radiological protection.*



Source: The authors

Subjected to radiation (Group 1)

In the first group are the components that will be submitted directly to ionizing radiation. These were selected so as to be resistant to such influence. This group can be defined as the whole structural and sensory part of the Slave arm. The parts composed of semiconductor materials such as controllers and other electronic circuits will remain in the other groups. The elements of the first group are:

• Mechanical elements of the Slave arm;

• Motors;

• Position sensors;

• Connection wiring of motors and sensors.

The Group-1 components are coupled to the second group of components via umbilical cable. Thus, it can send and receive data from the control electronics. The umbilical coupling has the function of preserving the second components group of the ionizing radiation influence. It can be shielded in order to protect it from radiation. The control electronics can be several meters from the manipulator. The umbilical cord is capable of being introduced into openings of 20 mm in diameter. This facilitates the equipment adaptation to already constructed hot cells.

<u>Radiation protected electronic components (Group 2)</u>

The second group is formed by the Slave arm control electronics. These elements are sensitive to ionizing radiation [4] [5]. They must therefore be packed in such a way as to maintain safe distance from the radiation source or even protected by specific shielding. This group consists of the following components:

• Voltage regulators;

• Bridges H;

• Arduino Nano [9], [12];

• Connection cabling.

Power supplies may also be included in this group. However, these can be several meters from the other components. This decreases the volume that must be shielded in cases of external applications (without using a hot cell).

<u>Master Arm (Group 3)</u>

This group is formed by elements of the Master arm that do not receive significant doses of radiation. This is coupled to the operator's body. The submission of these elements to radiation also means subjecting the human element. The following items are part of this group:

• Mechanical elements of the Master arm;

• Position sensors;

• Arduino Nano [9], [12];

• Voltage regulators;

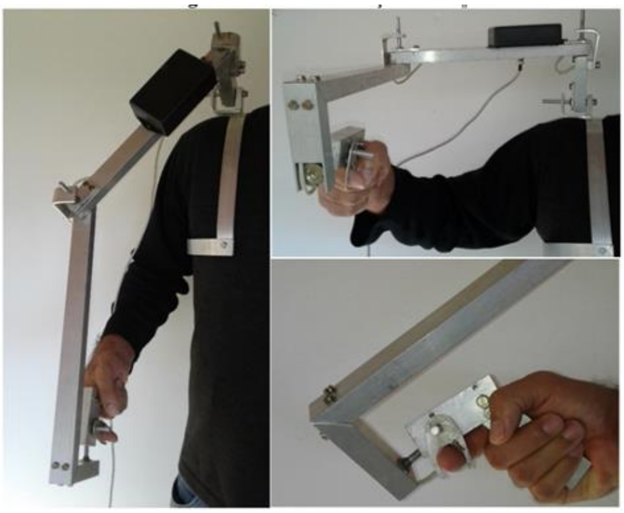
• Data cabling.

This group is connected to the second group via serial cable, which can be extend for 150 m. The cable transmits the commands from the master arm to the second group of components.

3. RESULTS AND DISCUSSION

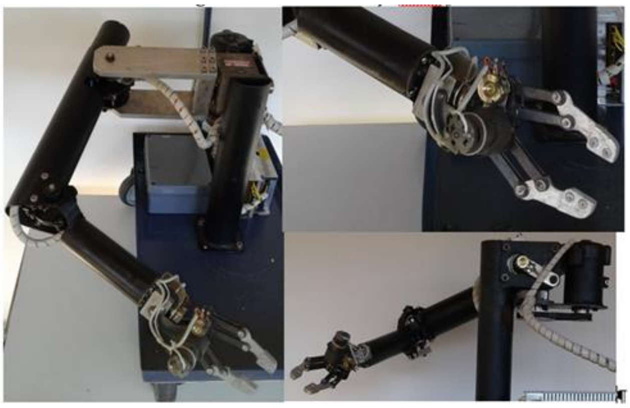
In this project it was developed a system of arm manipulator replicator of movements, with four degrees of freedom, plus the addition of a type clamp effector. It is remotely controlled using software programmable microcontrollers. Its command is performed through the Master-Slave system that performs operator arm movement replication. This handles the Master arm (Fig. 2) to control the Slave device (Fig. 3). The system was designed to withstand doses of ionizing radiation not tolerated by conventional electronic manipulators.

Figure 2: *Master arm.*



In the construction of the equipment, it was necessary to develop a servomotor system using sensors and motors resistant to ionizing radiation. Resistive sensors like potentiometer were used. These are able to interpret the position of its axis in the form of proportional voltage at the output, relative to the power supply. DC type motors with brushes were used, which only have electromechanical elements in their construction.

Figure 3: *Slave arm.*



For servo motors control a system of reading, communication, calculation and interpretation of information through a software that was specifically developed for it. The control is used to perform the positions interpretation of the device master arm joints and transmit commands to the Slave arm. This command is executed in the closed loop system, which uses feedback information from the sensors, to calculate the error in relation to the setpoint commanding the output. This control occurs through the PID controller. The system makes use of three Arduino Nano programmable platforms [12].

The control information leave the Master arm using serial output. This facilitates a future application of wireless control system. Serial output also increases the range of data transmission cabling used for communication (up to 150 m) without significant signal interference.

Three software were developed for the calculation of the movements and for communication between them. The programs were installed on three Arduino Nano platforms. A fault detection system is included to aid in the prevention of accidents caused by device defects.

3D modeling was performed aiming anatomical and anatomical dimensional similarity with the human arm. There were prioritized robustness, simplicity and ease maintenance. Standardized elements were used in the structure. The design was made to simplify manufacturing. Whenever possible, Computer Numeric Control - CNC laser cutting (application was used in the elements construction. The technical drawings greatly facilitated the construction of the prototype. Figure 4 shows a photograph of the operation of the prototype. Several tests were performed to evaluate the manipulator performance [7]. The tests performed are presented below.

Figure 4: *Operation with the manipulator*.

3.1 Work space

To find the working area of the manipulator in a quantitative way, the volume of the slave manipulator workspace was calculated.

A drawing was elaborated to obtain the area and the volume that comprises all the joint movements. The slave arm has been placed in all possible positions. The area and volume of action was calculated with the aid of the SolidWorks software. The test covered an area of approximately 0.63 m^2. Using this area an end-to-end sweep of the shoulder rotation joint was performed to produce a solid. The operating volume was 0.587 m^3.

3.2. Load Capacity

The load capacity was tested using a weight of 4.2 kg. The test was performed by raising the weight with the joints of the manipulator as far as possible. The purpose of the test was to verify the moment the joints are able to apply. The largest lever arm the equipment was capable of lifting the load of 4.2 kg was 430 mm. Thus, the momentum performed by the shoulder rotation joint was 17.8 Nm. The withdrawal and approximation and elbow flexion joints achieved the predicted performance being able to raise the weight of the test.

3.3. Performance of Controllers

The communication system performance and manipulator processing speed can influence controllers. It can be a factor that causes system instabilities. This can influence the operator's decision-making in trying to stabilize it. What can have the opposite effect and amplify the disturbances. This is due to the delay of the operator's actual situation perception of the system and the system analysis in relation to the operator's commands.

Unstable movements can also start due to the controllers actuation, that are affected by the execution speed of the control program. The controllers act by noting the positioning of the Slave handler with delay during the movement. A great delay for the programmer perceiving the set point approximation in addition to the complete programming cycle duration can be too much time [13]. This fact can cause a harmonic oscillation in the system that can be amplified by destabilizing the manipulator, or reducing over time until it reaches stability. This occurrence has as its source the PID controller itself that acts with corrective actions that destabilize the system. It will be working with data coming from the past of the Slave handler's history. But, far enough away to lose identity with the present. Response time was measured using a film of the Master and Slave manipulator in operation.

The images were later reproduced at 1/8 the recording speed. A time of 1.62 s was recorded between the action of the Master arm, in relation to the response time of the Slave manipulator. By multiplying the value obtained by the video reproduction rate, it was possible to calculate the real reaction time of the manipulator to a command, applying Equation 1, where TR is the actual recording time of the video:

$$T_R = 1/8 \times 1.62 = 0.2025 \text{ s.} \qquad (1)$$

This delay, approximately two-tenths of a second, may be difficult to perceive by the operator during the actions of the manipulator, especially those of greater amplitude. But, certainly not the same with the controllers, who are influenced by this delay. In some positions characterized by low joint load, oscillations that stop in periods of less than two seconds may occur most of the time.

Microcontrollers currently work at a communication rate of 115200 bauds[1] , which is the maximum supported by the chosen platforms. But, this does not prevent the growth of the speed of response of the system as a whole being improved, making improvements in the dynamics of programming execution.

The current model allows only one of the three microcontrollers to execute its programming at a time, allowing two controllers to remain idle at all times. This point is an opportunity to improve the control program so that it is able to cause the three controllers to execute their programming at the same time. This can dynimize the delay time by a factor of 1/3.

3.4. Transparency

Transparency refers to the operator's perception of the operating setting. As occurs in automaton robots, the greater the number of systems that aid the perception of the environment, the greater the capacity for successful interactions between the manipulator and the environment.

Effort feedback system

The manipulator was developed using a ring communication model with the purpose of favoring the use of feedback systems. Because sending information from the Slave arm to the Master arm occurs constantly. This communication can be used to send position information and Slave arm efforts to the Master handler. This information can be used to control the servomotors that can be installed in the Master arm and to apply forces to its joints.

One of the most used techniques to improve tele manipulator transparency is the use of feedback systems. This resource has the purpose of replicating the forces applied to the Slave

[1] Baud is the measure of the signal speed or events per second.

manipulator in the Master manipulator, so that the operator perceives these forces in the manipulation of the Master manipulator. By constructing a double hand system, where a force applied at one end is replicated in the other, as faithfully as possible. There is an improvement in the perception of operator immersion, with consequent improvement in the transparency of the system.

This function can be used for the operator to detect Slave hand collisions with the environment. A collision can be very disastrous in environments with manipulations involving hazardous and sensitive materials. This can aggravate the problem.

Precision

Tests were performed to measure the time that the operator is able to perform the effector positioning on the target and what is the deviation that the effector presents in the positioning. To measure the positioning a graduated ruler with a resolution of 1 mm was used. The dynamics of the test were to get as close as possible to the 15 cm mark in the center of the ruler starting from the region near the 25 cm marking.

By using the observed images it was possible to observe that during the manual operation of the equipment through the Master manipulator, the oscillations after the positioning of the effector have a maximum amplitude of ± 5 mm, being not different from all the stabilization attempts, the target position. It was also possible to observe that these oscillations occur frequently, appearing on average once per second alternating in direction.

The observed oscillations usually cease after a period of no more than eight seconds after the establishment of the desired position of the Master manipulator. This can be caused by delaying communication

4. CONCLUSION

The prototype is fully operational and able to perform object manipulations with great agility. Compared to similar models such as MT 200 TAO, this presents differentiated characteristics that can bring advantages [8]. It is possible to emphasize the use of sensing and actuation elements that have resistance to ionizing radiation superior to those used in the existing models. The equipment was built to facilitate adaptation in hot cell. This includes fixing your base to the floor or ceiling.

The control uses an umbilical cable with a diameter of less than 20 mm. It has small dimensions and weight that makes it portable, making it possible to use it in the field, being powered by 12 and 24 volt batteries. Compared to mechanical models, the equipment reduces operator fatigue and increases the possible operating distance.

The development in the field of remote manipulation in areas subjected to radiation is still quite fruitful. Encouraging the continuation of researches that until recently periods were in reduced rate. This work also exposes the need to elaborate more efficient systems able to operate submitted to fields of ionizing radiation of greater intensity.

It is still necessary to observe that for unstructured tasks remote manipulation remains the most viable option. Especially considering carrying out operations in hazardous environments that are less fault tolerant than they may entail in accidents.

ACKNOWLEDGMENT

This research project was supported by the following institutions: Nuclear Technology Development Center (CDTN), Brazilian Nuclear Energy Commission (Cnen), Research Support Foundation of the State of Minas Gerais (Fapemig), and Brazilian Council for Scientific and Technological Development (CNPq).

REFERENCES

[1] BALEN, T. R. **Effects of Radiation on Programmable Analog Devices (FPAAs) and Protection Techniques**. Doctoral Thesis. Universidade Federal do Rio Grande do Sul, Porto Alegre. 2013. (in Portuguese).

[2] BENNETT, P. C.; POSEY, L. D. **RHOBOT: Radiation Hardened Robotics**. Sandia National Laboratories, SAND97-2405 UC-51O. 1997.

[3] SHARP, R.; DECRETON, M. Radiation tolerance of components and materials in nuclear robot applications. **Reliability Engineering & System Safety**. V. 53, p.291-299. 1996. DOI: 10.1016/S0951-8320(96)00054-3.

[4] SCHRIMPF, R. D. Radiation Effects in Microelectronics. In: Velazco R., Fouillat P., Reis R. (eds). **Radiation Effects on Embedded Systems**. Springer, Dordrecht. 2007. DOI: 10.1007/978-1-4020-5646-8_2.

[5] SCHWANK, J. R. et al. Radiations effects in MOS oxides. **IEEE Transactions on Nuclear Science,** Snowmass Village. Vol. 55, n. 4, p.1833-1853, Aug. 2008. DOI: 10.1109/TNS.2008.2001040.

[6] HOUSSAY, L. P. Robotics and Radiation Hardening in the Nuclear Industry. Master Thesis. University of Florida. 2000.

[7] D` MARTINS, E. **Manipulator arm replicating movements of anatomical similarity applied to activities in ionizing radiation fields.** Master Thesis. Programa de Pós-Graduação em Ciência e Tecnologia das Radiações, Minerais e Materiais. Centro de Desenvolvimento da Tecnologia Nuclear. Belo Horizonte. 2018. (in Portuguese).

[8]. LACALHENE. MT200 TAO - **A new generation manipulator, fully electrically powered with software control**. Available at: https://www.lacalhene.com/int/applications-products/remote-manipulation/mt200-tao/. Accessed in: 06 April 2019.

[9]. ARDUINO. **Controles PWM**. Available at: www.arduino.cc/en/Tutorial/PWM. Accessed in: 10 April 2019.

[10] CAMPESTRINI, L. **Tuning of Decentralized PID Controllers Based on the Critical Point Method.** Master Thesis. Departamento de Engenharia Elétrica, Universidade Federal do Rio Grande do Sul. 2006. (in Portuguese).

[11] LA CALHÈNE. **MA-30 A compact remote manipulator for glove boxes and small cells**. Disponível em: https://www.lacalhene.com/int/applications-products/remote-manipulation/ma30/. Accessed in: 20 May 2018.

[12] ARDUINO. **Tech Specs**. Available at: https://store.arduino.cc/usa/arduino-nano. Acessed in: 08 April 2018.

[13] PHAM, H. L.; ADORNO, B. V.; PERDEREAU, V.; FRAISSE, P. Set-Point Control of Robot End-Effector Pose Using Dual Quaternion Feedback. **Robotics and Computer-Integrated Manufacturing.** Vol. 52: p. 100–110. 2018. DOI: 10.1016/j.rcim.2017.11.003.