Radiation-resistant robotic manipulator controlled by 6-DoF haptic control device to perform technological tasks in hot cells

V V Prikhodko¹, A A Sobolev¹, A V Zhukov¹, E M Chavkin¹, A N Fomin¹, V V Levshechanov¹, S V Pavlov² and V V Svetukhin³

¹S.P. Kapitsa Technological Research Institute of Ulyanovsk State University, 1/4 Universitetskaya emb., Ulyanovsk, 432017, Russia
²Sosny Research and Development Company, 4a Dimitrov Ave., Dimitrovgrad, Ulyanovsk region, 433507, Russia
³SMC “Technological Center”, 5 4806 str., Zelenograd, Moscow, 124498, Russia

E-mail: vp@kapitsa.tech

Abstract. The paper describes the results of developing a radiation-hardened robotic complex including the following original constituting elements: a robotic manipulator with a 2-finger gripper, a 6-DoF control device with force feedback, control software. The implementation of rotational motion of joints of the robotic manipulator through coaxial gear shafts resulted in its high resistance to ionizing radiation of up to $10^7$ Gy. The control device features high ergonomics similar to that of mechanical master-slave manipulators. The control software has a modular structure and contains both original and the state-of-the-art program components. A prototype of the robotic complex was built which demonstrated the capability of performing typical technological operations in a demo hot cell in both manual and automated modes.

1. Introduction

There is a number of industries where special equipment is used for remote operation in order to protect personnel from hazardous environments. The nuclear industry must be mentioned specifically due to extremely adverse health effects of ionizing radiation and the catastrophic consequences of possible emergencies.

The famous reactor meltdown that took place in Unit 2 at Three Mile Island served as a trigger for the development of nuclear robotics. Since then various types of robots have been created to assist man in contaminated areas, with much emphasis on mobile robots [1-4].

According to [5], potential applications involving the use of remote and robotic systems in radioactive environments include the following:

1) Civilian high level radioactive waste management;
2) Decontamination & decommissioning;
3) Radiation emergencies and/or accidents;
4) Fuel reprocessing.

In the field of research, a general purpose tool to work with radioactive isotopes has long been a mechanical master-slave manipulator (MSM) which reproduces the motion of the operator’s hand and performs the necessary tasks with its gripper [6, 7]. Master-slave manipulators are typically used in hot cells which are shielded chambers equipped with a viewing window and a couple of MSMs. The undeniable advantages of such manipulators are their high reliability and relative simplicity of design.
At the same time manipulators of this type have a limited set of operations like capture, retention, and movement of an object in the horizontal and vertical planes.

MSMs are widely used at Russian nuclear facilities for performing a wide range of technological operations [6] but now the manipulator park is becoming worn out due to the suspension of their domestic production. A possible solution could be a gradual replacement of old MSMs with robotic complexes which could expand the capabilities of MSMs by adding comfortable remote control, possibility to work with heavy loads, automation of routine tasks. At the moment, in Russia, this area is practically not covered by robotization despite some attempts [8]. There exist radiation-hardened robotic manipulators on the market such as A1000, Telbot by HWM [9] but their use in Russia is limited due to their relatively high price.

The paper describes the results of the research, design and production of a robotic complex with enhanced radiation resistance commissioned by one of Russian nuclear enterprises.

2. Materials and methods
In accordance with the technical requirements document, the robotic complex should include a 6-DOF manipulator arm equipped with a 2-finger gripper, a control device with force feedback, an operator control panel and a control server with integrated control software.

The robotic manipulator must provide a service area inside a 1m x 1m x 1m chamber with unloading area in the far wall. The manipulator arm should have one translational degree of freedom in the upper joint and rotational degrees of freedom in other joints. The load capacity at a maximum reach should be 10 kg.

The manipulator arm inside a hot cell should be capable to work with radioactive material with the total accumulated dose of no less than 10⁴ Gy. This requirement led to a decision of locating the actuators outside the hot cell and implementing the rotational motion of joints through coaxial gear shafts – similar to the approach implemented in Russian master-slave manipulators MEM-10 [6]. The use of stainless steel as a base material, in theory, allows increasing the radiation resistance of the manipulator arm up to 10⁵ Gy.

The control device requirements implied that, on the one hand, 6-DoF ergonomics similar to that of the mechanical MSMs should be provided, and on the other hand, the functionality of MSMs should be expanded by adding controls to provide scaling and automated modes of motion.

The control server was assigned to implement the following tasks:
a) collecting data from the control device and providing feedback to the operator in real time;
b) collecting data about the current state of the manipulator and errors;
c) controlling the actuators of the robot in real time;
d) providing a graphical operator interface.

The control software for the robotic complex was designed on a modular basis and employed both original and the state-of-the-art program components. Ubuntu 16.04 OS with Linux-RT 4.4.0 real-time kernel was installed on the server. The direct and inverse kinematics problem, dynamics problem and collision problem were solved using ROS Kinetic middleware and its ROS-MoveIt and ROS-Industrial extensions.

The Qt / PyQt library was the main tool for implementing the operator’s GUI. The program code of the robot control process was implemented in C / C ++ / Python. Among the third-party open-source software modules are used in the development of the RTK, the following can be highlighted: MoveIt for solving the inverse kinematic problem, Gazebo simulator with its powerful physical solver, and RViz as the visualization tool. These allowed carrying out a preliminary simulation of the movements of the manipulator along the optimal trajectory in a limited space of the hot cell.

The design of the robotic complex hardware was performed in SolidWorks.

A number of numerical simulations were conducted in the ANSYS software. By means of the ANSYS Rigid Body Dynamics module, a comprehensive simulation analysis of the kinematic diagram of the manipulator, its stability and the occurrence of mechanically forbidden states was performed. The
problem of reducing the mass of the manipulator without deteriorating its strength characteristics was also addressed by means of ANSYS.

The metal parts of the robotic complex were fabricated at Alpha-Universal Ltd., Ulyanovsk, Russia. The industrial EtherCAT network protocol was chosen as the real-time communication technology. Festo EMMS-AS-70-S-LS-RRB servos were used together with Festo CMMP-AS-C2-3A-M3 controllers.

3. Results and discussion

The generalized diagram of the proposed robotic complex is shown in Figure 1. The robotic complex consists of the following elements: a robotic manipulator, a control device with force feedback; a control panel with hardware buttons and a touch screen; a server with control software; a servos control cabinet; a power cabinet.

The manipulator is a 6-link 6-DOF robotic arm with a 2-finger gripper having the following features:

1) To ensure high resistance to ionizing radiation, the drives are placed in the base of the robot arm outside the hot cell and are made in the form of separate quick-detachable units.

2) Mechanical transmission of rotational motion from the drive unit to the wave gearbox is implemented through coaxial gear shafts and backlash-free bevel gears to reduce the positioning errors of the robotic arm.

3) Resolvers are used as feedback sensors in drive units. They are less susceptible to the damaging effects of ionizing radiation in comparison with semiconductor optical encoders.

The kinematic diagram of the manipulator is shown in Figure 2a.

![Figure 1. Generalized diagram of the robotic complex.](image-url)
Figure 2. Kinematic diagrams: (a) manipulator arm; (b) control device – delta robot with a spherical joystick unit on top of the moving platform: 1 – ball-screw actuator, 2 – motor drive, 3 – platform, 4 – spherical joystick unit.

Kinematic simulation in ANSYS gave the following specifications for the joints of the manipulator:

- movement along A1 axis: 200 mm;
- rotation around A2 axis: 360°;
- rotation around A3 axis: ± 110°;
- rotation around A4 axis: 360°;
- rotation around A5 axis: 360°;
- rotation around A6 axis: 360°;
- movement along A7 axis (gripper pusher stroke): 16 mm;
- gripper stroke: 80 mm.

The control device was built on the basis of the delta robot (tripod) model [10] which is a modified version of a Gough–Stewart platform [11, 12] with three electric linear actuators. Its kinematic diagram is shown in Figure 2b, the general view is illustrated in Figure 3a. The principle of parallel kinematics is used here which ensures high rigidity of the system and accuracy of geometric displacements with a relatively small mass of moving parts. The tripod includes 3 identical linear actuators driven by servomotors each placed at some angle to the base. The moving platform is supported by 3 pairs of rods attached to the carriages of the linear actuators.

In addition to motion, the platform provides an imitation of resistance to movement when reaching a predetermined boundary of the working area, and also provides accelerated or decelerated motion of the platform depending on the force applied by the operator to load cells (tensoreistive sensors).

The platform provides 3 degrees of freedom. Another 3 degrees of freedom (rotational) are produced by a spherical joystick unit located on top of the moving platform (Figures 2b and 3b). Inside the rotating sphere, there is a handle that is a force application point for both translational and rotational motions. The handle has a locking lever, which has the function of locking/unlocking the movement of the sphere. The block of buttons on the handle has one switch and three buttons, each with its own individual
function: “Automatic movement to the given position”, “Automatic movement to the initial position”, “Desync”.

Figure 3. Mechanical part of the control device: a – general view of the control device; b – joystick unit inside a rotating sphere.

The device base is a welded structure to which the tripod is fastened. Mounted on the base are servo drivers, power supplies and a control board. The base also encloses the control server and a UPS. The front panels are made of sheet metal and are removable for an easy access to hardware. The base itself rests on 4 adjustable legs that are secured to the floor with anchor fasteners.

The control software for the robotic complex was designed on a modular basis and employed both original and the state-of-the-art program components. The functional diagram of the motion control software modules is shown in Figure 4. The dashed line in Figure 4 highlights the subroutines that are part of the developed ROS node. The node receives information from the controller board about the position of the moving elements of the control device and computes the current position in Cartesian coordinates. Then it checks whether the joystick is in the workspace. In case of moving beyond this region, the algorithm forms resistance (feedback) to the movement of the operator’s hand. The debug module allows testing and calibration procedures.

The information about the spatial position of the platform with a joystick installed on it, analog signals from load cells and control commands are transmitted to an Atmel SAM3X8E microcontroller with ARM Cortex-M3 architecture. Original algorithms for processing the information were developed that solve the direct and inverse kinematic problems of the tripod device. In addition to the low-level task of managing servomotors, the microcontroller provided two-way communication channel with the ROS middleware using the UART protocol.

A prototype of the robotic complex was manufactured and installed in a demo hot cell. The control process was tested in two main modes:

a) manual control mode, in which the control of the robot is performed directly by the operator through the control device;

b) an automated control mode in which the control of the robot is performed by the control computer. This mode implements predetermined types of motion such as automatic movement to the given position and automatic movement to the initial position.
4. Conclusion

The robotic complex consisting of several original elements was presented. A prototype of the robotic complex was manufactured which demonstrated the capability of performing typical technological operations in a demo hot cell in both manual and automated modes. The modular approach to designing the control software allowed minimizing the cost of the solution, providing a high level of safety and automating a number of service functions.

The results of the research showed that the robotic complex can replace outworn mechanical master-slave manipulators and increase the efficiency of technological operations in hot cells while maintaining high radiation resistance.

Acknowledgements

The research was supported by the Ministry of Science and Higher Education of the Russian Federation, project RFMEFI57417X0173.

References

[1] Shin H, Kim C H and Lee H H 2013 Development of a Snake Robot for Unstructured Environment J. of Korea Robotics Society 8(4) 247-255
[2] Seo Y, Jeong K, Shin H, Choi Y, Lee S U, Noh S, Kim T W and Cho J W 2016 A Mobile Robotic System for the Inspection and Repair of SG Tubes in NPPs Int. J. of Advanced Robotic Systems 13(2) 1-8
[3] Tsitsimpelis I, Taylor C J, Lennox B and Joyce M J 2019 A review of ground-based robotic systems for the characterization of nuclear environments Progress in Nuclear Energy 111 109-124
[4] Jung S H, Kim Ch H and Seo Y Ch 2007 The Development of a Radiation Hardened Robot for Nuclear Facilities (Republic of Korea: N. p.)
[5] Bennett P C and Posey L D 1997 RHOBOT: Radiation hardened robotics (United States: N. p.)
[6] Yurevich E I 2010 Foundations of Robotics (Saint Petersburg: BKhV-Peterburg)
[7] Jayarajan K and Singh M 2006 Master-Slave Manipulators: Technology and Recent Developments BARC News Letter 269 2-12
[8] Voynov I V, Kazantsyev A M, Morozov B A and Nosikov M V 2018 Radiation-hardened manipulators and methods of expanding their functional capabilities Proc. of the Int. Sci. and Technological Conf. "Extreme robotics and conversion tendencies" June 7-8, 2018, Saint-Petersburg, Russia pp 114-125
[9] Manipulators and robots for the nuclear, oil and gas industries. Available at: https://www.hwm.com.
[10] Lopez M, Castillo E, García G and Bashir A 2006 Delta robot: inverse, direct, and intermediate Jacobians Proc. IMechE 220 Part C: J. Mechanical Engineering Science 103-109

[11] Stewart D 1965 A platform with six degrees of freedom Proc. Institution of mechanical engineers (London) vol 180 pp 371–86

[12] Lebret G, Liu K and Lewis F L 1993 Dynamic analysis and control of a Stewart platform manipulator J. Robotic Systems 10 629–55