Design and Development of Mobile Robot for Radiation Protection Assistance

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Summary
A mobile Radiation Protection Assistant Robot (RPAR) has been designed to assist radiation workers in a hostile radiation environment. The RPAR comprises of a cubicle tri-wheeled platform and a four Degree of Freedom (4-DOF) serial type articulated robotic arm. The movement of the platform is controlled by two differential wheeled driving systems. The RPAR is helpful in radiation mapping, handling and transportation of radioactive material. It can also be helpful in radiation emergencies. The kinematics study and manipulator Jacobian of the gripper of articulated robotic arm has been assessed and workspace analysis is made. Radiation hardening study of the electronic components of RPAR driver modules has also been carried out to ensure the safe operation up to a total ionizing dose of 9 Sv.
Key words:
Articulated robotic arm, Kinematics, radiation, Remote handlings.

1. Introduction

Among the main applications of robot and robotic devices are automation and repeatedly precise work. Due to this reason, robot is a very useful supporting tool in many fields such as nuclear industry. Usually, profitability is the first motivation to switch over from a regular mass-production work to an automated system. However, in nuclear industry, safety of the radiation worker is preferable and is of greatest importance. The reactor engineering and design demands very narrow design tolerances for quality control to make the nuclear reactor almost risk free and as safest as possible. Even with tight quality controls and design specifications, the frequency of inspection and maintenance is to be increased due to aging factor of a nuclear instillation. On the other hand due to technical reasons, the shutdown period of a nuclear reactor cannot be prolonged. Further more, it is worth mentioning that most of the nuclear installations have limited workspaces. In an emergency situation, the narrow working space obstructs the radiation worker to work freely within a restricted time period. Hence, the limitations increase the risk of unwanted radiation exposure.

As the standard permissible dose limit for a radiation worker is 20 milli-Sivert (mSv) per annum [1]. Therefore, usually, it is quite difficult to meet the required dose limit due to the workspace and time limitations. It has been noted that the workers dose cost more than $500,000 per man-Sv [2]. Therefore, robotics is the only solution and compensation for these expenses by replacing the human radiation workers to meet the concept of ALARA (As Low As Reasonably Achievable) [3]. The robots and robotic devices can perform their task for longer period without the risk of unwanted exposure due to radiation.

The mobile Radiation Protection Assistant Robot (RPAR) as shown in Fig.1 is designed and constructed for the radiation workers to help them in hazardous environment for longer durations. To achieve maximum performance and utilization of RPAR, it is necessary to determine its controllability, kinematics, workspace analysis and manipulator Jacobian. This work presents the radiation hardening study, kinematics modeling, workspace analysis and manipulator Jacobian of a RPAR.

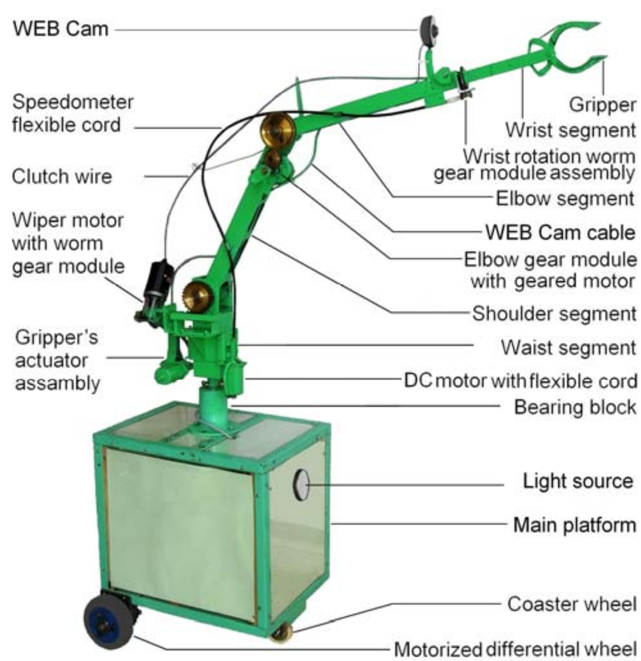

Fig. 1 Radiation Protection Assistant Robot (RPAR)

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2. Robot Design and Fabrication

2.1 The Mobile RPAR

The RPAR comprises of a controllable mobile platform having 4-Degree-of-Freedom (4-DOF) articulated robotic arm. It utilizes computer vision camera for remote handling and tele-operation. The RPAR is a multipurpose robotic system capable of executing variety of tasks in hazardous radiation environment.

2.2 Mechanics

The RPAR platform is a cubicle frame built with 2.5 cm square MS pipe (L= 51cm, W= 38cm, H=46cm). Two neoprene hard rubber wheels (ϕ150.0 mm) are directly fixed to two independently controlled dc wiper motors to provide a differential wheel driving system to the platform. The third wheel is a caster wheel (ϕ 80.0 mm). Two differentially driven wheels and a caster wheel produce a controllable tri-wheeler configuration.

The articulated robotic arm is fixed in the middle of the top surface of RPAR platform. It comprises of four segments. (i) Waist (7.62 cm (L) x 7.62 cm (W) x 40.6 cm (H)). (ii) Shoulder (5.1 cm (L) x 5.1 cm (W) x 46.1 cm (H)). (iii) Elbow (3.8 cm (L) x 3.8 cm (W) x 43.2 cm (H)). (iv) Wrist (2.5 cm (L) x 2.5 cm (W) x 33.2 cm (H)). Each segment has independent controllable mechanical system.

The pivot joint of the waist is a shaft fixed in a bearing block on the top of the RPAR platform. The lower end of shaft is attached with a worm gear module assembly, which is directly coupled to a dc wiper motor shaft. The waist of the articulated robotic arm is fixed on the upper end of the bearing-block shaft.

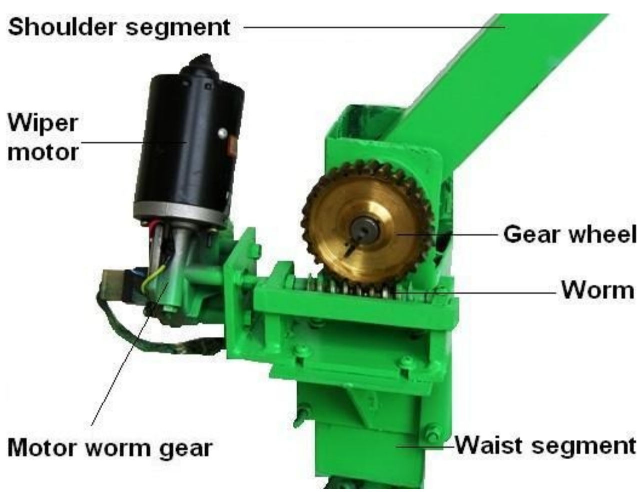

Fig. 2 Worm geared module assembly

Double worm gear arrangement gives a good controllability in movements and a high torque output yield. The angular (sweep) movement of waist is restricted within 340^o range with the help of two micro-switches for necessary working area coverage. The pivot joint of the waist-shoulder segment is at a height of 101.5 cm from the floor level. The pivot joint for waist-shoulder segments is also provided with a similar double worm gear module assembly as shown in Fig.2. The up-down movement of the shoulder is limited within 123^o range. The pivot-joint for shoulder-elbow segments is provided with a dc worm geared motor coupled with a spur gears module, as shown in Fig. 3. The up-down movement of elbow segment is limited within 210^o. The wrist segment is a part of elbow segment and is provided with an especially designed gripper for a secure gripping of different objects.

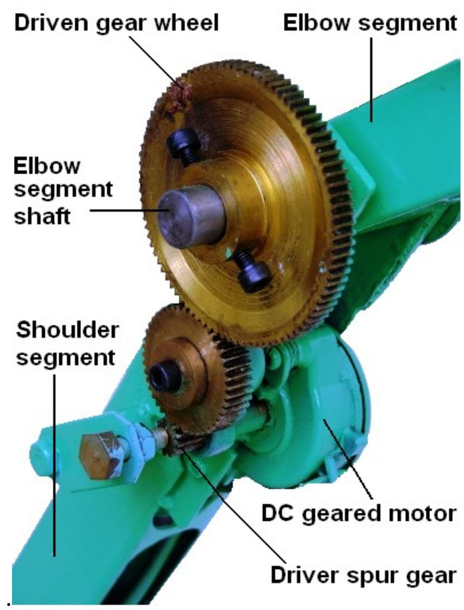

Fig. 3 Spur gear module assembly

The gripper can handle an object having maximum weight 2100g and size in range from 0.35 mm to 120 mm, which is useful to pick and carry an accidentally dropdown radioactive material/sources. The wrist rotation is limited within 270^o.

Encoder assemblies are incorporated for precise positioning, control and displacement of platform and the movements of the articulated robotic arm The encoder disk of different sizes and number of optic slits were made locally to be used for optical encoder assemblies. The optical encoder assemblies have been interfaced to the onboard slave computer through serial port (RS-232) via an interfacing card. The onboard (slave) computer and tele-computer (master) are interconnected with the help of Wireless

Ethernet by using a Wireless access point (D-link, DWL-2100AP, 802.11g), It communicates at 108Mbps maximum data transfer rate. The main controller interfacing board of the platform, articulated robotic arm and other driving module circuits are well shielded by double walled Lead jacket filled with mineral oil to minimize the effect of ionizing and scattering radiations. This helps to safeguard the electronics of the onboard computer.

2.3 Software architecture

High-level language (Microsoft Visual Basic V6.0) is used to develop robotic interfacing and controlling program (Fig. 4). All inputs for driver modules are controlled through a parallel port, However, the encoder's interfacing card is connected to the serial port to assess the encoder inputs and eventually keeping the backup records of all the movements of RPAR platform and the articulated robotic arm.

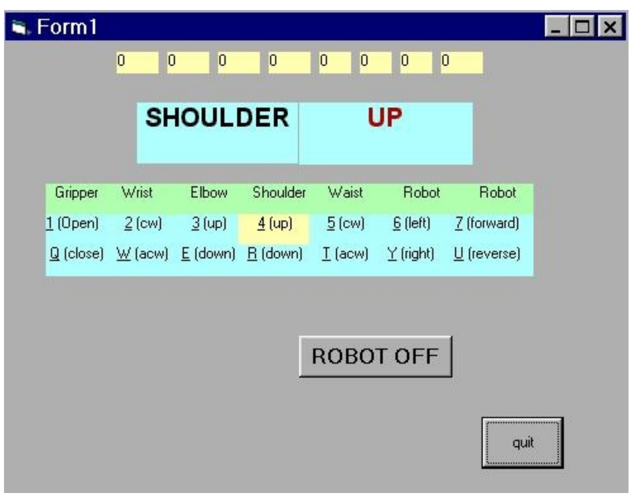

Fig. 4 Robotic interfacing and controlling program

The software simultaneously controls the following four tasks.

(i) Communication between main tele-computer (master) and the onboard (slave) computer via built-in Wireless Ethernet facility.
(ii) Positioning and movement control of the platform and the articulated robotic arm from optical encoders.
(iii) Tele monitoring through onboard camera.
(iv) To keep the positioning and movement data record for correction and positioning of the robot and its control functions.

The RPAR system is also controllable through an operator's remote console whenever the direct site visibility is available.

3. Radiation hardening study

Radiation hardening study [4] became obvious in 1962 when the Telstar I satellite failed as a result of radiation in the Van Allen Belts [5]. Therefore, due to damaging effects of radiation, it is necessary to study the maximum radiation dose limit or stability tolerance of the electronic components. This limit is assumed as hardening limit of electronic circuitry. Finding this hardening limit is essential to determine the reliability and to get maximum performance of the devices. An experiment was conducted to assess the stability and radiation hardening limits of the RPAR. The H-Bridge Module (HBM) in operational conditioned was exposed to radiations in an experiment. The experimental setup comprised of a power supply, motor with load and HBM driver module. An ammeter was connected to observe the current behavior of the electronic module during gamma radiation exposure. The module was exposed to a gamma source of 29 TBq Cobalt-60 Tele-therapy units at the Second Secondary Dosimetry Laboratory (SSDL), Health Physics Division, PINSTECH. The current behavior response of the HBM in the radiation field is shown in Fig. 5. The performance of the HBM electronic was carefully checked before and after irradiation. During irradiation experiment it has been observed that no prominent change occurred up to an integrated dose of 9 Sv. The relay logic modules were also subjected for the similar radiation hardening study but no significant effect was observed at the same dose.

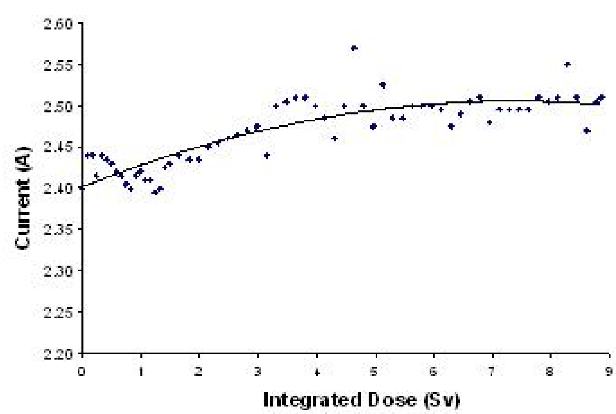

Fig. 5 Current behavior of HBM under gamma radiation exposure

4. Kinematics study

To achieve better controllable performance of the robotic devices, the kinematics and workspace analysis is essential. The Kinematics refers to the properties of geometrical movements with reference to the gripper-tip of fixed points in links regardless of their masses or the forces acting on them. The kinematics study is vital for the evaluation of the controllability and precise positioning of the robotic platform and articulated robotic arm's gripper-tip. Two modes of kinematics have been considered to evaluate the effective performance of the RPAR articulated robotic arm.

4.1 Forward kinematics

The forward kinematics of the articulated robotic arm of RPAR is concerned with the transformation of position or momentary orientation information in the joint-space to Cartesian-space [6]. The forward kinematics is described by equation (1);

$$r(t) = f(\theta(t)) \qquad (1)$$

Where

$\theta(t)$ = m-vector of joints variables

$r(t)$ = n-vector of Cartesian variables

$f(\cdot)$ = Continuous non-linear function whose structure and parameters are known for a given manipulator.

By assigning the link-frames according to the Denavit-Hartenberg (DH) Convention [7], the forward kinematics for RPAR articulated robotic arm are derived. In D-H convention notation, the d_i units is translation or offset along Z_i from the X_{i-1}, θ_i degrees rotation about Z_i of X_{i-1} into X_i in the right-hand sense, α_i degrees is a rotation or twist about axis X_{i-1} of Z_{i-1} into Z_i in the right-hand sense and b_i units is a displacement along X_{i-1} from Z_{i-1} to Z_i. The out-of-plane axis can be obtained by using the right-hand rule on each pair of link-axis. The generalized rotation matrix R_{i-1}^{i} is the directional cosine matrix relating link-frame i to link-frame j and can be derived through the Eq. (2).

$$R_{i-1}^{i} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & b_i \\ \cos\alpha_i \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i & -d_i \sin\alpha_i \\ \sin\alpha_i \sin\theta_i & \sin\alpha_i \cos\theta_i & \cos\alpha_i & d_i \cos\alpha_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

The D-H parameters for RPAR articulated robotic arm have been determined according to the information available in the literature [8] and are given in Table 1.

Table 1: D-H parameters for RPAR articulated robotic arm

DH Parameters \ Link	1	2	3	4
α_i	0^0	90^0	0^0	90^0
b_i	0	0	e	f
θ_i	θ_1	θ_2	θ_3	θ_4
Di	h	0	0	0

For RPAR: e =46.1, f = 76.4 and h =101.5 cm.

The schematic geometrical diagram of the articulated robotic arm is shown in Fig.6.

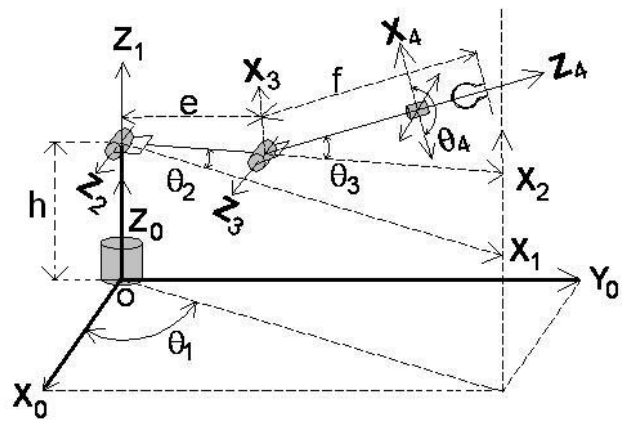

Fig. 6 Geometry of RPAR articulated robotic arm.

The R_{i-1}^{i} is rotation matrix of positions and orientation of each link and is given as in the following matrix;

$$R_0^1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & h \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad R_1^2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_2^3 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & e \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad R_3^4 = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & f \\ 0 & 0 & -1 & 0 \\ \sin\theta_4 & \cos\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The resulting expression for position orientation of the gripper tip with respect to the elbow, R_0^4 is calculated from [9, 10] and given by the Eq. (3).

$$R_0^4 = R_0^1 R_1^2 R_2^3 R_3^4 \qquad (3)$$

$$R_0^4 = \begin{bmatrix} c_1c_4c_{23} + s_1s_4 & -c_1s_4c_{23} + s_1c_4 & c_1s_{23} & fc_1c_{23} + ec_1c_2 \\ s_1c_4c_{23} - c_1s_4 & -s_1s_4c_{23} - c_1c_4 & s_1s_{23} & fs_1c_{23} + es_1c_2 \\ c_4s_{23} & -s_4s_{23} & -c_{23} & fs_{23} + es_2 + h \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where c_i denotes $cos(\theta_i)$ and s_i denotes $sin(\theta_i)$.

The position equation of the gripper-tip can be expressed as follows;

$$\begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \begin{bmatrix} f\cos\theta_1\cos\theta_{23} + e\cos\theta_1\cos\theta_2 \\ f\sin\theta_1\cos\theta_{23} + e\sin\theta_1\cos\theta_2 \\ f\sin\theta_{23} + e\sin\theta_2 + h \end{bmatrix} \quad (4)$$

4.2 Inverse kinematics

The inverse kinematics helps to find the pivot-joint variables for desired position and orientations of the gripper tip by inverse mapping of the forward kinematics [11]. The inverse kinematics equation is given by Eq. (5).

$$\theta(t) = f^{-1}(r(t)) \quad (5)$$

The inverse kinematics involves the existence and uniqueness of a solution and determines method for its effectiveness and efficiency. The inverse kinematics calculations are difficult and become more compounded due to requirement of real-time solutions of feedback information during robotic operations. However, in real-time solution the procedure for calculations of inverse kinematics for redundant manipulators are very important in robotics and used for the inverse kinematics calculation for RPAR articulated robotic arm.

Inverse kinematics calculations for RPAR articulated robotic arm determined particular values of the waist rotation angle θ_1, the shoulder segment up-down movements θ_2 and the elbow segment up-down movements θ_3, by putting the theta values the resultant for a known position of gripper tip is given below;

$$(D^4_{x0}, D^4_{y0}, D^4_{z0}) = (P_x, P_y, P_z)$$

The positional equations (6-12) for the RPAR articulated robotic arm are found to be:

$$f\cos\theta_1 \cos\theta_{23} + e\cos\theta_1\cos\theta_2 = P_x \quad (6)$$

$$f\sin\theta_1\cos\theta_{23} + e\sin\theta_1\cos\theta_2 = P_y \quad (7)$$

$$f\sin\theta_{23} + e\sin\theta_2 + h = P_z \quad (8)$$

$$e\cos\theta_2 + f\cos\theta_{23} = \cos\theta_1 P_x + \sin\theta_1 P_y \quad (9)$$

$$\cos\theta_1 P_y - \sin\theta_1 P_x = 0 \quad (10)$$

$$e + f\cos\theta_3 = \cos\theta_2(\cos\theta_1 P_x + \sin\theta_1 P_y) + (P_z - h)\sin\theta_2 \quad (11)$$

$$f\sin\theta_3 = -\sin\theta_2(\cos\theta_1 P_x + \sin\theta_1 P_y) + (P_z - h)\cos\theta_2 \quad (12)$$

These are nontrivial and unrepeated positional relations.

By solving the positional equations, the values of θ_1, θ_2 and θ_3 are as follows;

$$\theta_1 = A\tan 2\left(\frac{P_y}{P_x}\right) \quad (13)$$

$$\theta_2 = A\tan 2\left(\frac{(P_z - h)(e + f\cos\theta_3) - f\sin\theta_3\sqrt{P_X{}^2 + P_Y{}^2}}{(P_z - h) f\sin\theta_3 + (e + f\cos\theta_3)\sqrt{P_X{}^2 + P_Y{}^2}}\right) \quad (14)$$

$$\theta_3 = A\tan 2\left(\frac{\pm\sqrt{4e^2 f^2 - [(P_z - h)^2 + P_x^2 + P_y{}^2 - e^2 - f^2]^2}}{(P_z - h)^2 + P_x^2 + P_y^2 - e^2 - f^2}\right) \quad (15)$$

4.3 Manipulator Jacobian

The performance of the articulated robotic arm segments (manipulator's segments) depends on their controllability and pivot limitations. These can be evaluated by manipulator Jacobian. This matrix represents infinitesimal change in position relationship between the joint displacements and the gripper tip location at newly acquired position and the arm segment configuration [12]. The Jacobian of 4-DOF manipulator is given as;

$$J = \begin{bmatrix} -s_1(ec_2 + fc_{23}) & -c_1(es_2 + fs_{23}) & -fc_1s_{23} \\ c_1(ec_2 + fc_{23}) & -s_1(es_2 + fs_{23}) & -fs_1s_{23} \\ 0 & fc_{23} + c_2e & fc_{23} \\ 0 & s_1 & s_1 \\ 0 & -c_1 & -c_1 \\ 1 & 0 & 0 \end{bmatrix} \quad (16)$$

As the elements of the Jacobian are functions of joint displacements, therefore, varies with the arm's segments (links) configuration. For instant three joints of RPAR articulated robotic arm move at joint-velocities $\dot{\theta} = [\dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3]^T$, $v = [\dot{x}, \dot{y}, \dot{z}]^T$ will be the resulting gripper-tip velocity vector. By taking derivative of $\begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix}$ with respect to *t*, the Eq. (4) becomes;

$$\frac{dDx}{dt} = j\frac{d\theta}{dt}$$

that is,

$$V = J\dot{\theta} \quad (17)$$

Thus the manipulator Jacobian determines the velocity relationship between the joints and the gripper-tip. J_1, J_2 and J_3, are three 3 x 1 vectors for the first, second and third columns of the Jacobian, respectively. The Eq. (17) can be written as

$$V = J_1\dot{\theta}_1 + J_2\dot{\theta}_2 + J_2\dot{\theta}_3 \quad (18)$$

Each column of the Jacobian represents the gripper-tip velocity vector generated by the corresponding joint motion at unit velocity while all other joints are immobilized. The resultant gripper-tip velocity is given by summing the three vectors.

4.4 Workspace Analysis

The robot's workspace is also an important criterion for manipulator (articulated robotic arm) output working performance. The reachable workspace for RPAR articulated robotic arm is depicted as in Figs 7 to 9. The two dimensional geometrical view while waist segment is stationary is illustrates in Fig. (7). The arc ***a′b*** has maximum accessible workspace thickness i.e. 14.26 cm. The arc ***aa′*** has tapered workspace which is gradually increases up to point **a′**, while arc ***bb′*** has a sharp upward decreases in workspace area. Maximum and minimum edge boundaries of gripper-tip workspaces have been evaluated by putting certain limitation of θ_1, θ_2 and θ_3.

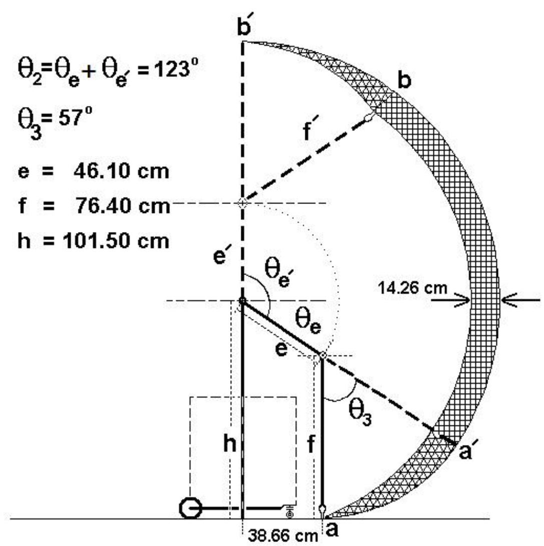

Fig. 7. 2-Dimensional maximum and minimum edge boundary diagram

The maximum workspace is generated by applying the "Algorthim-1" in which θ_1 is varied from 0^o to 340^o, θ_2 is varied from 0^o to $\theta_e + \theta_e^{/}$ (123^o) and $\theta_3 = 0^o$ (i.e. elbow is linear to shoulder) as shown in Fig. 8.

Algorithm-1: Maximum Workspace $(\theta_3 = 0^o, \Delta\theta_1, \Delta\theta_2)$

Input: $\theta_3 = 0, \Delta\theta_1, \Delta\theta_2$ (grid steps of angles θ_1, θ_2)

Output: X, Y, Z (3D Plot)

for θ_1 *= 0 to 340 step* $\Delta\theta_1$

for θ_2 *= -33 to 90 step* $\Delta\theta_2$

$$X(\theta_1,\theta_2,\theta_3) = f\cos\theta_1\cos\theta_{23} + e\cos\theta_1\cos\theta_2$$
$$Y(\theta_1,\theta_2,\theta_3) = f\sin\theta_1\cos\theta_{23} + e\sin\theta_1\cos\theta_2$$
$$Z(\theta_1,\theta_2,\theta_3) = f\sin\theta_{23} + e\sin\theta_2 + h$$

next θ_2

next θ_1

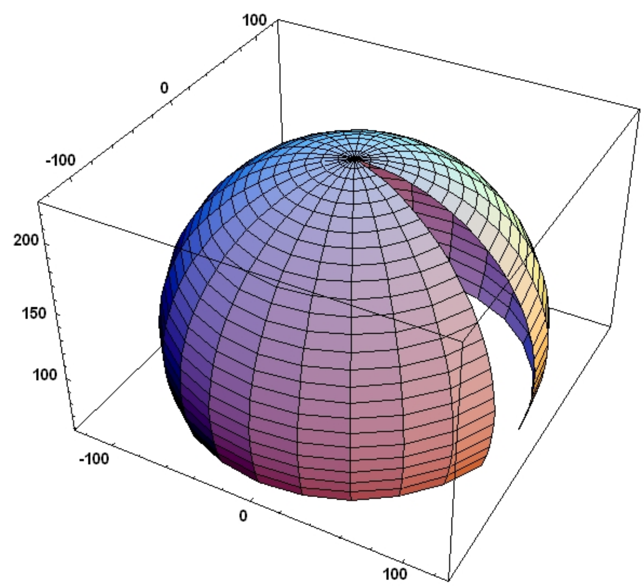

Fig. 8 3-Dimensional maximum workspace diagram

Minimum workspace is generated by applying the "Algorthim-2" in which θ_1 is varied from 0^o to 340^o, θ_2 is varied from 0^o to $\theta_e + \theta_e^{/}$ and θ_3 is fixed at 57° as shown in Fig. (9). The assessable three dimensional workspace surfaces for gripper-tip, therefore, can be generated by applying different conditional algorithms.

Algorithm-2: Minimum Workspace $\boldsymbol{\theta_3 = 57^o}, \Delta\theta_1, \Delta\theta_2)$

Input: $\theta_3 = 57^o, \Delta\theta_1, \Delta\theta_2$ (grid steps of angles θ_1, θ_2)

Output: X, Y, Z (3D Plot)

for θ_1 *= 0 to 340 step* $\Delta\theta_1$

for θ_2 *= -33 to 90 step* $\Delta\theta_2$

$$X(\theta_1,\theta_2,\theta_3) = f\cos\theta_1\cos\theta_{23} + e\cos\theta_1\cos\theta_2$$
$$Y(\theta_1,\theta_2,\theta_3) = f\sin\theta_1\cos\theta_{23} + e\sin\theta_1\cos\theta_2$$
$$Z(\theta_1,\theta_2,\theta_3) = f\sin\theta_{23} + e\sin\theta_2 + h$$

next θ_2

next θ_1

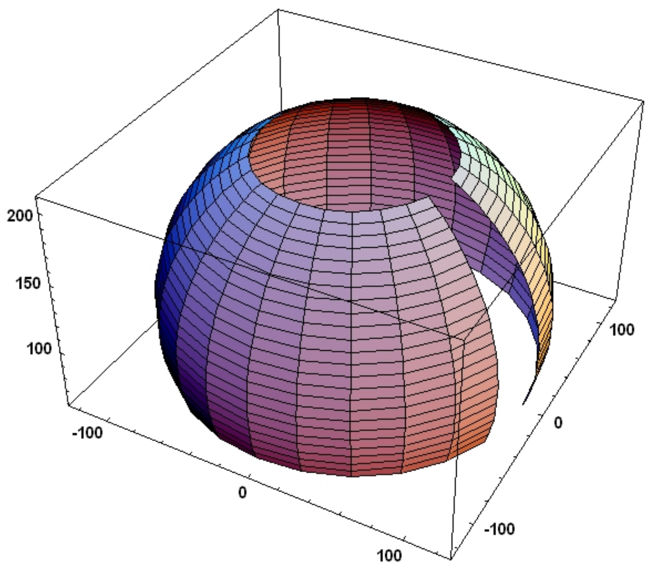

Fig. 9 3-Dimensional minimum workspace diagram.

5. Conclusions

In a nuclear installation the congested work space and restricted time period is problematic to work freely. RPAR has been designed and developed to assist radiation workers in those areas of nuclear installation that are beyond the safe approach for human. To achieve better performance of a robotic device, kinematics and the manipulator Jacobian analysis are the most important considerations for maximum utilization of an articulated robotic arm system either with fixed or mutable platform. Forward and inverse kinematics, manipulator Jacobian and workspace range of the RPAR articulated robotic arm is anticipated. The experiment of RPAR has been carried out to compare the actual positioning control and the calculated Kinematics and Jacobian Manipulator analysis. The results indicate a 97% agreement. The deviation and error in repeatability of RPAR performance is possible due to technical problems such as less precise mechanical work and job accuracy, uncontrollable latch effect in the moving parts particularly in the gear modules etc. However, present study demonstrates that it is possible to develop a cost effective robotic device (RPAR) with most of the locally available commercial components. This is a successful step towards developing devices to assist radiation worker in a hazardous radiation environment for safety and to avoid radiation exposure risk. The robot has been tested in radiation environment and found operating satisfactory. The robot is operational at PINSTECH for handling radioactive materials, radiation mapping and wipe testing of sealed radiation sources.

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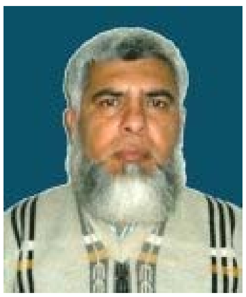

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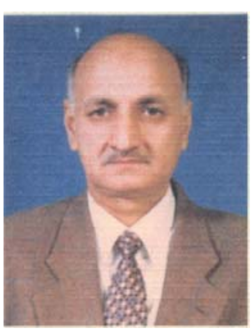

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