PROGRAMMING 3 DOF INDUSTRIAL ROBOTS WITH NATURAL HAND MOTIONS: AN IMPEDANCE CONTROL APPROACH

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Abstract

Programming industrial robots is a complex and time-consuming task that requires skilled operators. To simplify this process, this study proposes a method for programming a 3 DOF robot using natural hand motions. During the robot learning phase, the human operator holds and moves the robot's endpoint to the desired position, and saves it without using force/torque sensors. The impedance controller coefficients are then adjusted to minimize the gravity effects to zero, ensuring seamless movement of the robot without resistance. It has been observed that the reaction forces on the human hand are very low except for the singular position of the robot, where the reaction forces increase. During the operating mode, the robot's endpoint visits the sequential positions taught by the human, and the Bees Algorithm is used to optimize the impedance controller coefficients based on simulations. The proposed method is flexible and can be applied to various tasks, making it suitable for a wide range of applications. Simulation results demonstrate the effectiveness of this method, highlighting its potential to enhance the performance of industrial robots when interacting with the environment. The optimized impedance controller ensures precise movements, and the proposed method offers several advantages over traditional programming methods, such as reduced programming time and improved ease of use. Overall, this study presents a promising solution to the challenges of programming industrial robots using natural hand motions, offering a more efficient and user-friendly approach that can enhance productivity and improve product quality. Further research is needed to explore the potential of this method in more complex tasks and environments.

Keywords: Robot programming, 3 DOF robot, impedance control, The Bees Algorithm, hand gestures

1. INTRODUCTION

Programming industrial robots is a complex and time-consuming task that requires skilled operators. In many industrial applications, the robot manipulator needs to interact with the environment to achieve the desired task, such as pushing, polishing, cleaning, and grinding. However, controlling the interaction between the robot and the environment can be challenging [1, 2]. One effective approach to regulate this dynamic relationship is through impedance control. Impedance control aims to regulate the relationship between the force and position of the robot's end effector in contact with the environment [3-5]. This approach ensures that the robot manipulator endpoint follows both the desired force profile and the desired position accurately [6-8]. In impedance control, the trajectory function of the robot's end effector is an essential factor that affects the dynamic relationship between the robot and the environment [9, 10].

To simplify the process of programming industrial robots, this study proposes a method for programming a 3 DOF robot using natural hand motions. During the robot learning phase, the human operator holds and moves the robot's endpoint to the desired position and saves it without using force/torque sensors. The impedance controller coefficients are then adjusted to minimize gravity effects to zero, ensuring seamless movement of the robot without resistance [11]. The proposed method is flexible and can be applied to various tasks, making it suitable for a wide range of applications.

Optimization algorithms are a fundamental tool used in many scientific fields to solve complex problems. Two categories of optimization algorithms exist: global optimization algorithms and local search algorithms [12]. Global optimization algorithms, such as Genetic Algorithm [13, 14], Particle Swarm Optimization [15], and The Bees Algorithm [16-18], are designed to explore the entire solution space to find the global optimum. In contrast, local search algorithms such as Hooke-Jeeves [19] and Newton Raphson [20] focus on exploring local regions of the solution space to identify the optimum. The choice of which optimization algorithm to use depends on the nature of the optimization problem and the characteristics of the solution space [21]. Impedance controller parameters can be optimized using the Bees Algorithm [6, 8, 22]. By using the optimized impedance controller, the robot can perform its task accurately and efficiently, reducing the risk of errors and improving productivity in various industrial applications.

Simulation results demonstrate the effectiveness of this method, highlighting its potential to enhance the performance of industrial robots when interacting with the environment. The optimized impedance controller ensures precise movements, and the proposed method offers several advantages over traditional programming methods, such as reduced programming time and improved ease of use. Overall, this study presents a promising solution to the challenges of programming industrial robots using natural hand motions, offering a more efficient and user-friendly approach that can enhance productivity and improve product quality.

2. MATHEMATICAL MODEL

This research focuses on a 3 degree-of-freedom (DOF) manipulator, which comprises three joints. The physical configuration of the manipulator consists of three links, each with individual masses denoted as s m_1, m_2, and m_3, as illustrated in Figure 1.

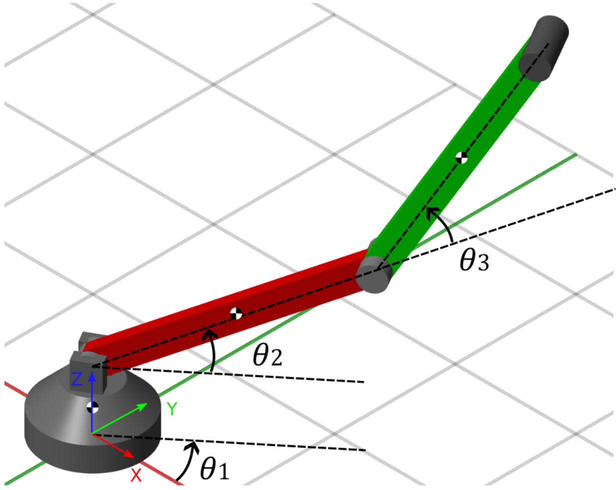

Figure 1. 3 dof robotic system

Forward kinematics is a widely used technique for determining the spatial position of a robot's end-effector relative to a reference coordinate system. A systematic approach to this technique was introduced by Denavit and Hartenberg [23], which involves obtaining a homogeneous transformation matrix through a series of sequential transformations. These transformations include a d-translation along the z-axis, a θ-rotation about the z-axis, an a-translation along the x-axis, and an α-rotation about the x-axis, as expressed by Equations (1) and (2).

$$^{i-1}A_i = T_z(d)R_z(\theta)T_x(a)R_x(\alpha) \tag{1}$$

$$^{i-1}A_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Table 1 presents the Denavit-Hartenberg (D-H) parameters of the 3 DOF robot. These parameters are used to describe the kinematic relationship between the robot's joints and end-effectors.

Table 1. D-H Parameters for a 3 DOF Robot

i	***d*** **[mm]**	***θ*** **[°]**	***a*** **[mm]**	***α***[°]
1	d_1	0	0	$\pi/2$
2	0	L_2	0	0
3	0	L_3	0	0

According to Equation (3), the center of mass for each body is defined with respect to its own coordinate system.

$$\begin{aligned} ^1r_1 &= [0 \quad 0 \quad -d_1/2]^T \\ ^2r_2 &= [-L_2/2 \quad 0 \quad 0]^T \\ ^3r_3 &= [-L_3/2 \quad 0 \quad 0]^T \end{aligned} \tag{3}$$

According to the methodology described in reference [24], the actuator torque for the i-th joint can be calculated using Equation (4). The acceleration-related symmetric matrix is defined in Equation (5) and its properties have been discussed in previous research [24, 25]. The impedance torque acting on the i-th joint is represented by τ_{ei}. The velocity matrix, denoted as U_{ij}, represents the velocity of the i-th body with respect to the j-th joint angle, commonly denoted as θ_j. This matrix is defined using Equation (6), which provides a formal expression for the relationship between the body's velocity and the joint angle.

$$M(q)\ddot{\theta}_i + C(\theta_i, \dot{\theta}_i) + G(\theta_i) = \tau_{act,i} + \tau_{ei} \tag{4}$$

$$M_{ik} = \sum_{j=max(i,k)}^{n} Tr(U_{jk} J_j U_{ji}^T) \tag{5}$$

$$U_{ij} = \begin{cases} {}^{0}A_{j-1} \; Q \; {}^{j-1}A_i & ,j \le i \\ 0 & ,j > i \end{cases} \tag{6}$$

The derivative of a homogeneous matrix ‘A’ can be calculated by left multiplying it with the Q matrix. The Q matrix represents the rotational component of the transformation matrix for revolute joints and is defined by Equation (7). The use of the Q matrix is essential for determining the derivative of the homogeneous matrix ‘A’, which is a crucial step in the kinematic analysis of robotic systems.

$$Q = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

Equation (5) employs the trace operator, denoted by Tr, to compute the sum of a matrix’s diagonal elements. This mathematical tool is frequently used in linear algebra and has been previously defined by Fu et al. [24] and Weisstein [26]. Equation (8) provides a concise mathematical definition of the trace operator.

$$Tr(a) = \sum_{i=1}^{n} a_{ii} \tag{8}$$

The torques τ_{act1}, τ_{act2}, and τ_{act3} can be determined by expanding the equation of motion given in Equation (4). By further expanding Equations (9) through (11), the torques required to generate the system’s observed motion can be calculated.

$$\begin{aligned} \tau_{act1} = & -\frac{1}{12}(12m_3 + m_1)L_2^2\dot{\theta}_1\dot{\theta}_2 sin(2\theta_2) - \frac{1}{12}(\dot{\theta}_2 + \dot{\theta}_3)L_3^2\dot{\theta}_1 m_2 sin(2\theta_2 + 2\theta_3) \\ & - \frac{1}{2}L_2L_3\dot{\theta}_1\dot{\theta}_3 m_3 sin(\theta_3) - \frac{1}{2}d_1 g m_1 sin(\theta_1) + \frac{1}{2}L_2L_3cos(2\theta_2 \\ & + \theta_3)\dot{\theta}_6 m_3 + \frac{1}{24}((12m_3 + m_1)L_2^2 + (12m_3 + m_1)L_2^2 cos(2\theta_2) \\ & + 12L_2L_3cos(\theta_3)m_3 + 24I_1 + L_3^2 m_2)\dot{\theta}_6 + \frac{1}{24}L_3^2 cos(2\theta_2 + 2\theta_3)\dot{\theta}_6 m_2 \\ & + \frac{1}{4}(2m_3 + m_2)L_2cos(-\theta_2 + \theta_1)g + \frac{1}{4}(2m_3 + m_2)L_2cos(\theta_1 + \theta_2)g \\ & + \frac{1}{4}L_3cos(-\theta_2 - \theta_3 + \theta_1)gm_3 + \frac{1}{4}L_3cos(\theta_1 + \theta_2 + \theta_3)gm_3 - (\frac{1}{2}\dot{\theta}_3 \\ & + \dot{\theta}_2)L_2L_3\dot{\theta}_1 m_3 sin(2\theta_2 + \theta_3) \end{aligned} \tag{9}$$

$$\begin{aligned}\tau_{act2} = &-\frac{1}{2}L_2L_3\dot{\theta}_3^2 m_3 sin(\theta_3) - \frac{1}{4}((2m_3 + m_2)L_2 + L_3cos(\theta_3)m_3)cos(-\theta_2 \\ &+ \theta_1)g - \frac{1}{4}L_3gm_3sin(-\theta_2 + \theta_1)sin(\theta_3) - \frac{1}{4}L_3gm_3sin(\theta_1 \\ &+ \theta_2)sin(\theta_3) + \frac{1}{2}((\frac{1}{12}(12m_3 + m_1)L_2 + L_3cos(\theta_3)m_3)L_2 \\ &+ \frac{1}{12}L_3^2cos(2\theta_3)m_2)\dot{\theta}_1^2 sin(2\theta_2) + \frac{1}{2}(\frac{1}{12}L_3m_2sin(2\theta_3) \\ &+ L_2m_3sin(\theta_3))L_3cos(2\theta_2)\dot{\theta}_1^2 + \frac{1}{24}((2m_1 + 24m_3)L_2^2 + 2L_3^2m_2 \\ &+ 24L_2L_3cos(\theta_3)m_3)\dot{\theta}_5 + \frac{1}{24}(12L_2L_3cos(\theta_3)m_3 + 2L_3^2m_2)\dot{\theta}_4 \\ &+ \frac{1}{4}((2m_3 + m_2)L_2 + L_3cos(\theta_3)m_3)cos(\theta_1 + \theta_2)g \\ &- L_2L_3\dot{\theta}_2\dot{\theta}_3m_3sin(\theta_3)\end{aligned} \tag{10}$$

$$\begin{aligned}\tau_{act3} = &-\frac{1}{4}L_3cos(-\theta_2 - \theta_3 + \theta_1)gm_3 + \frac{1}{12}L_3^2\dot{\theta}_4m_2 + \frac{1}{2}L_2L_3\dot{\theta}_2^2m_3sin(\theta_3) \\ &+ \frac{1}{24}(12L_2L_3cos(\theta_3)m_3 + 2L_3^2m_2)\dot{\theta}_5 + \frac{1}{24}L_3^2\dot{\theta}_1^2m_2sin(2\theta_2 + 2\theta_3) \\ &+ \frac{1}{4}L_2L_3\dot{\theta}_1^2m_3sin(2\theta_2 + \theta_3) + \frac{1}{4}L_2L_3\dot{\theta}_1^2m_3sin(\theta_3) + \frac{1}{4}L_3cos(\theta_1 \\ &+ \theta_2 + \theta_3)gm_3\end{aligned} \tag{11}$$

3. IMPLEMENTATION OF IMPEDANCE CONTROL

Figure 2 illustrates the schematic representation of the impedance control methodology. The implementation involves calculating the robot's desired interaction point position using forward kinematics and inverse dynamics equations based on joint angles. Any deviation between the derived position and the target position is converted into an interaction force by multiplying it by the spring constant and damping coefficients. This force is then multiplied by the transpose of the Jacobian matrix to generate joint torques. The final torque transmitted to the robot is obtained by combining these computed torques with those derived from the impedance control approach, ensuring efficient system control.

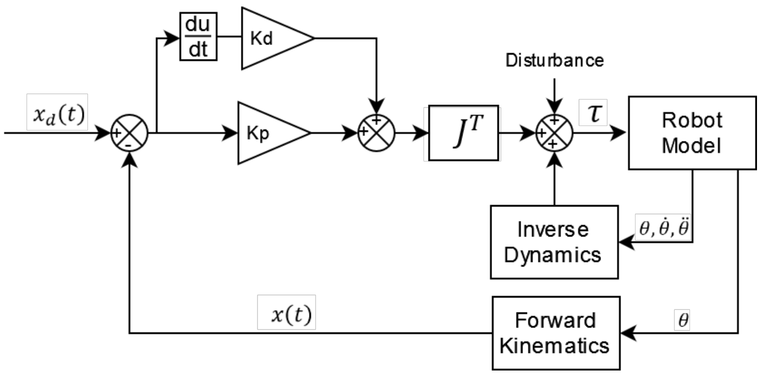

Figure 2. Diagrammatic illustration of the implementation of impedance control approach for robotic systems.

The interaction force generated by the Proportional-Integral-Derivative (PID) control method is mathematically expressed in Equation (12).

$$F_{int} = k\begin{bmatrix} x_{3d} - x_3 \\ y_{3d} - y_3 \\ z_{3d} - z_3 \end{bmatrix} + b\begin{bmatrix} \dot{x}_{3d} - \dot{x}_3 \\ \dot{y}_{3d} - \dot{y}_3 \\ \dot{z}_{3d} - \dot{z}_3 \end{bmatrix} + i\int\begin{bmatrix} x_{2d} - x_2 \\ y_{2d} - y_2 \\ z_{3d} - z_3 \end{bmatrix}dt \tag{12}$$

In this study, to enable the manual programming of point locations through human hand movements, the impedance control parameters must be set to zero. As a result, the k, b, and i coefficients are set to zero. Since the interaction force becomes zero, the human operator can move the robot's endpoint with minimal reaction forces.

The impedance torques are also zero due to the zero interaction forces. As a result, the total torques acting on the system are solely the actuator torques, as derived from Equations (9) through (11).

4. NUMERICAL APPLICATION

This investigation concentrates on a robot system with specific physical parameters, including $d_1 = 0.2625\,m$, $L_2 = L_3 = 1\,m$ and $m_1 = m_2 = m_3 = 5\,kg$. The human operator manually moves the endpoint of the 3 DOF robot from point 1 to point 8 in a sequential manner using their hand, as depicted in Figure 3. At each point, the human operator records the location of the point to program the 3 DOF robot.

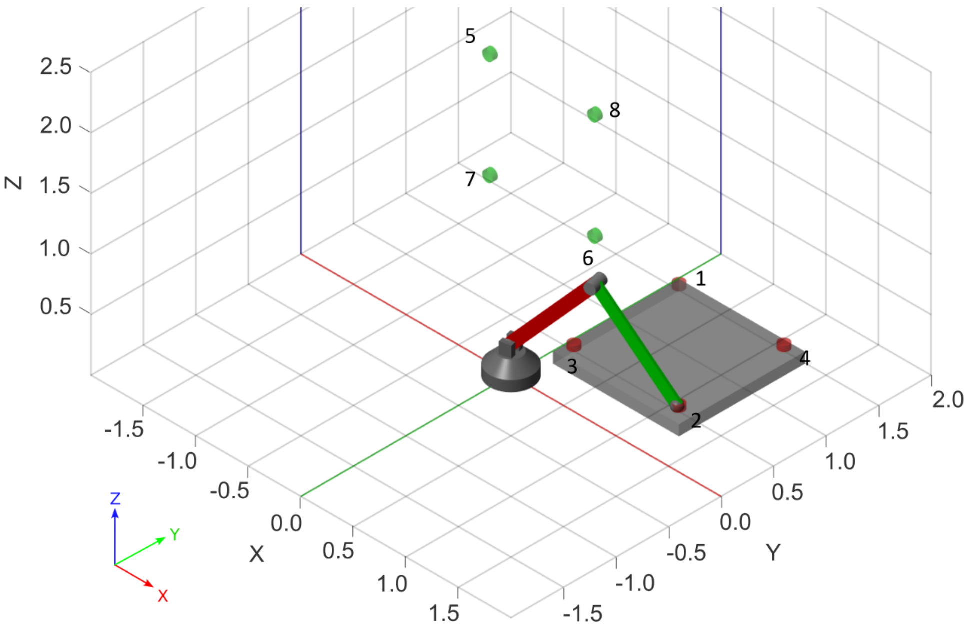

Figure 3. Numerical depiction of the robot system and desired programming locations of the human operator

The desired location of programming points from point 1 to point 8 is provided in Table 2.

Table 2. Desired Locations of Programming Points.

Point No	X [m]	Y [m]	Z [m]	Point No	X [m]	Y [m]	Z [m]
1	0.3	1.3	0.25	5	-1.2	1	1.55
2	1.3	0.3	0.25	6	-0.2	1	0.55
3	0.3	0.3	0.25	7	-1.2	1	0.55
4	1.3	1.3	0.25	8	-0.2	1	1.55

3. RESULTS AND DISCUSSION

The reaction force of the robot's endpoint to human hand during the programming is shown in Figure 4.

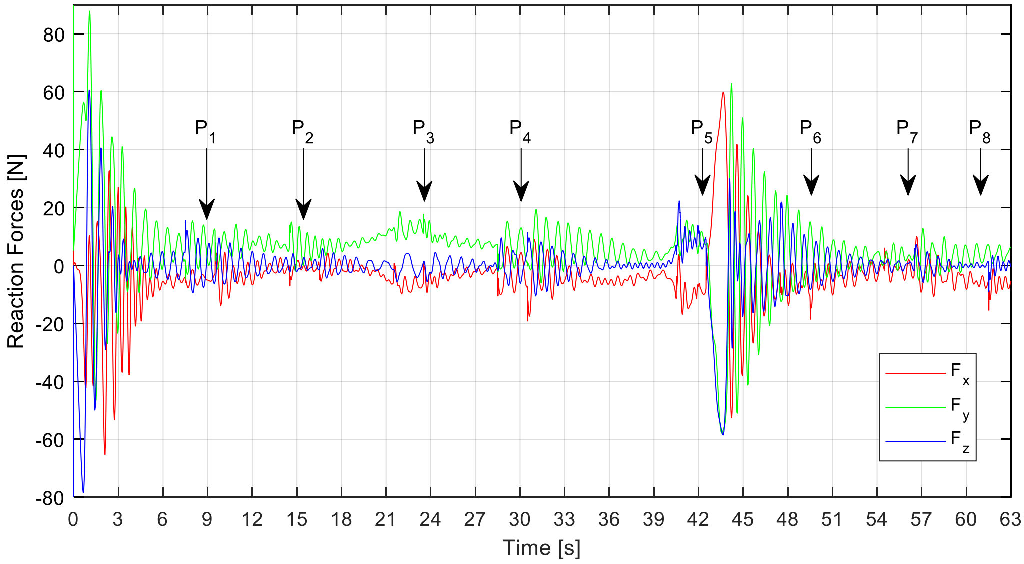

Figure 4. Reaction forces acting on the human hand

Just prior to singularity positions such as P_4 and P_5, the reaction forces and positional errors significantly increase. Figure 5 displays the positional errors between the desired and actual endpoint locations.

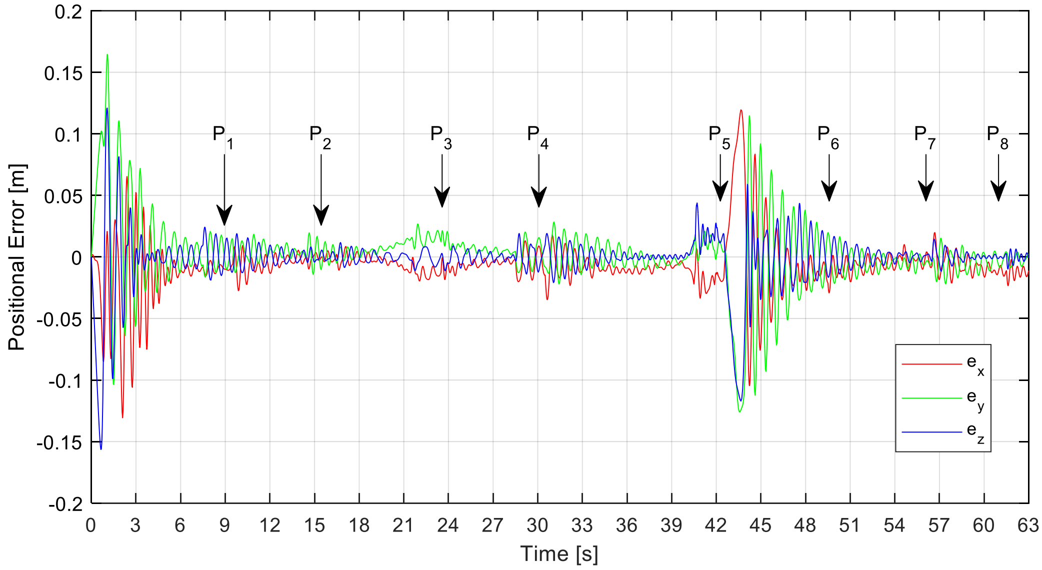

Figure 5. Robot's endpoint positional errors between on desired and actual position

The final positions of the robot during the scenario are depicted in Figure 6.

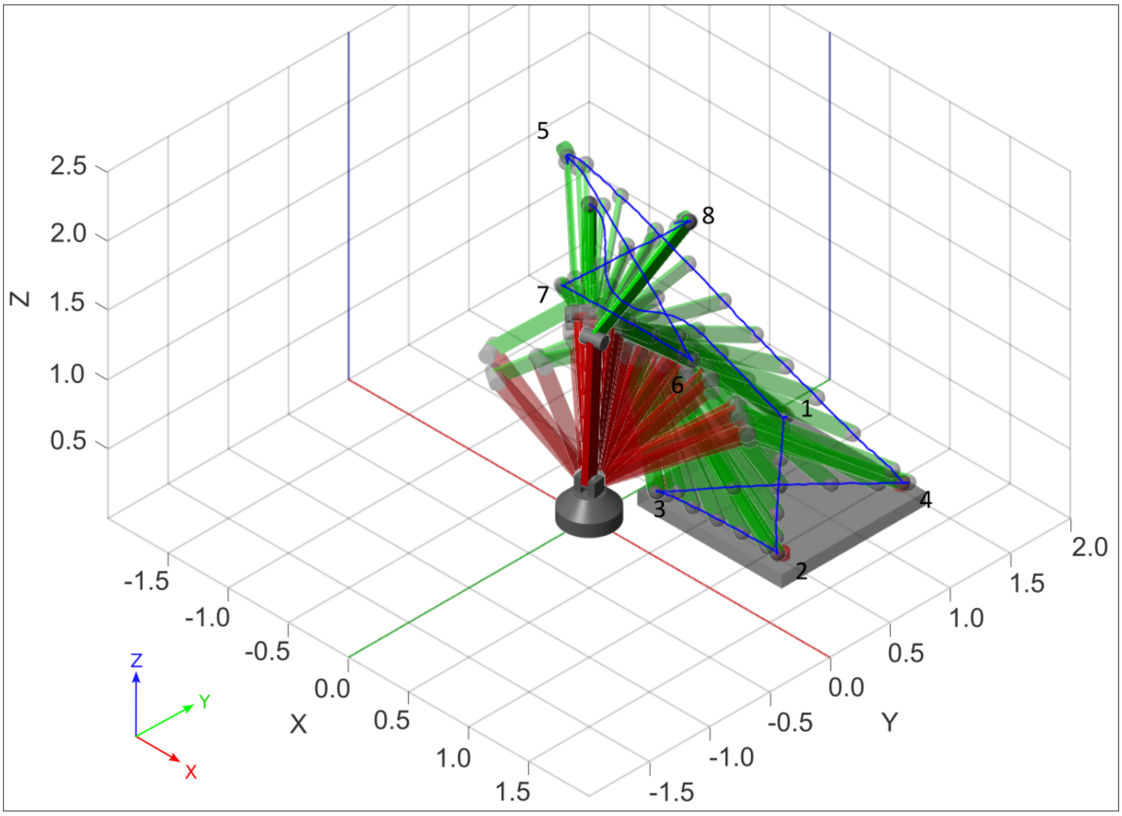

Figure 6. Movement of the robot's endpoint

CONCLUSIONS

In this study, an approach for programming a 3 DOF robot using natural hand motions was proposed. The approach involves a learning phase during which the human operator guides the robot's endpoint to the desired position and records it without the use of force/torque sensors. Torques are applied to the robot's joints to counteract the effects of gravity and achieve zero interaction forces, resulting in seamless movement with minimal resistance. During the programming mode, reaction forces on the human hand were generally observed to be around 10 N, with increases up to 80 N at the robot's singularity positions. Positional errors were typically between 0 and 0.05 m, with increases up to 0.15 m at singularity positions.

The proposed approach is versatile and effective in enhancing the performance of industrial robots. It offers advantages such as reduced programming time and improved ease of use. This study presents a promising solution for programming industrial robots using natural hand motions. Further research is needed to minimize reaction forces and positional errors at the robot's singularity positions.

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