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Design, Analysis and Development of a 6-DOF Robotic Manipulator for Manufacturing Automation

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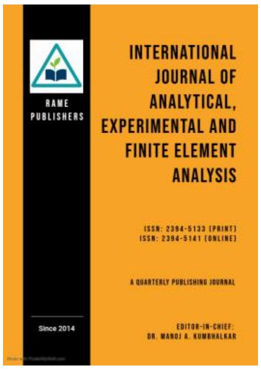

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Abstract: Industrial automation increasingly demands flexible and cost-effective robotic systems capable of performing complex manufacturing operations. This research presents the design, modelling, kinematic analysis, and simulation of a robotic manipulator developed for industrial automation applications. A complete three-dimensional CAD model of the manipulator was created and analyzed to achieve the desired workspace, payload capacity, and motion characteristics. Forward and inverse kinematic models were formulated using the Denavit–Hartenberg (D-H) convention to establish the relationship between joint parameters and end-effector position and orientation. The developed robotic system was simulated using RoboDK and validated through virtual motion studies to evaluate trajectory generation, reachability, and operational performance. Structural assessment of critical components was performed using Finite Element Analysis (FEA) to ensure adequate stiffness and load-carrying capability under working conditions. The simulation results demonstrated smooth joint coordination, accurate end-effector positioning, and reliable path execution within the designated workspace. The structural analysis confirmed that the designed manipulator operates within permissible stress and deformation limits, ensuring safe and stable operation. The proposed methodology integrates CAD modelling, kinematic analysis, simulation, and structural validation into a unified framework for robotic manipulator development. The outcomes of this work demonstrate the feasibility of developing an efficient and economical robotic system suitable for material handling, welding, inspection, and other industrial automation tasks. The study provides a foundation for future integration of advanced control algorithms, vision systems, and real-time industrial applications.

Keywords: Robotic Manipulator, Industrial Robot, Forward Kinematics, Inverse Kinematics, RoboDK, CAD Modelling, Finite Element Analysis, Industrial Automation.

1. Introduction

Industrial automation has become a key driver of productivity, quality, and operational efficiency in modern manufacturing industries. Robotic manipulators play a vital role in automation by performing repetitive, hazardous, and precision-based tasks such as welding, material handling, assembly, inspection, and machine tending. The ability of robotic systems to operate continuously with high accuracy has significantly increased their adoption across various industrial sectors.

A robotic manipulator consists of interconnected links and joints that provide controlled motion to position and orient an end-effector within a defined workspace. Among various configurations, six-degree-of-freedom (6-DOF) robotic arm manipulators for automation or for welding operation are widely used because they offer complete positional and orientation control, enabling them to perform complex industrial operations with high flexibility. The performance of a robotic manipulator depends on its structural design, workspace capability, payload capacity, kinematic accuracy, and control strategy.

The design and development of robotic manipulators require the integration of mechanical design, kinematic modelling, structural analysis, and simulation tools. Kinematic modelling establishes the relationship between joint variables and end-effector motion, while simulation platforms enable trajectory verification and workspace analysis before physical implementation. Structural assessment is equally important to ensure that the manipulator can withstand operational loads without excessive deformation or failure.

In the present study, a 6-DOF robotic manipulator is designed and analyzed for manufacturing automation applications. Three-dimensional CAD models are developed and evaluated using kinematic analysis, simulation studies, and Finite Element Analysis (FEA). The proposed approach provides a systematic framework for the development and validation of robotic manipulators suitable for industrial automation and future smart manufacturing applications.

2. Literature Review

Considerable research has been devoted to the design, modelling, analysis, and control of robotic manipulators for industrial automation applications. Denavit and Hartenberg [1] introduced the Denavit-Hartenberg (D-H) convention, which remains the most widely adopted method for modelling robotic kinematics. Craig [2] presented comprehensive methodologies for forward and inverse kinematic analysis, establishing the foundation for modern robotic manipulator design. Siciliano et al. [3] extensively investigated robotic system modelling, motion planning, and control strategies, highlighting the importance of accurate kinematic and dynamic formulations in industrial robots.

Spong et al. [4] developed analytical approaches for robot dynamics and control, demonstrating the significance of dynamic modelling in improving trajectory tracking performance. Corke [5] introduced simulation-based robotic analysis using MATLAB and robotics toolboxes, enabling efficient validation of manipulator kinematics and workspace characteristics. Niku [6] studied industrial robot configurations and demonstrated that six-degree-of-freedom manipulators provide superior flexibility and orientation control compared to lower degree-of-freedom systems.

Tsai [7] investigated robotic manipulator design methodologies and emphasized the importance of workspace optimization and structural stiffness in industrial applications. Angeles [8] examined manipulator performance measures and identified kinematic accuracy and dexterity as critical parameters influencing robot effectiveness. Shah and Dhananjay [9] performed CAD modelling and kinematic analysis of a six-axis robotic manipulator using simulation tools and reported satisfactory positioning accuracy within the desired workspace. Kumar et al. [10] utilized Finite Element Analysis (FEA) to evaluate structural behaviour of robotic arms and observed that proper material selection and geometric optimization significantly reduce deformation under payload conditions.

Recent studies have focused on integrating simulation platforms such as RoboDK, ROS, and digital twin technologies for robot development and validation. Researchers have demonstrated that virtual simulation environments reduce development time, improve trajectory planning, and enhance system reliability before physical implementation. However, despite significant advancements in robotic manipulator design and simulation, the development of cost-effective industrial robotic systems with optimized structural performance, accurate kinematic modelling, and efficient simulation-based validation remains an active area of research. This study addresses these challenges through the design, analysis, and simulation of a 6-DOF robotic manipulator intended for manufacturing automation applications.

3. Problem Statement and Objectives

3.1 Problem Statement

Industrial robotic manipulators are increasingly used in manufacturing applications such as welding, material handling, assembly, and inspection. However, commercial industrial robots are often expensive and may not be optimized for specific application requirements. The design of a robotic manipulator involves challenges related to workspace coverage, payload capacity, positional accuracy, structural rigidity, and motion control. Inadequate structural stiffness can result in excessive deformation, reduced positioning accuracy, and poor operational performance under loading conditions.

A six-degree-of-freedom (6-DOF) robotic manipulator offers enhanced flexibility and complete control over the position and orientation of the end-effector. However, the development of such systems requires accurate kinematic modelling, structural validation, and simulation-based performance evaluation. These aspects can be effectively analyzed using CAD modelling, kinematic analysis, simulation tools, and Finite Element Analysis (FEA) to ensure reliable operation in industrial environments.

3.2 Objectives

- Develop a parametric 3D CAD model of a 6-DOF robotic manipulator.
- Establish forward and inverse kinematic models using the Denavit–Hartenberg (D-H) convention.
- Perform workspace analysis to evaluate the reachability and motion capability of the manipulator.
- Simulate robot motion and trajectory planning using RoboDK.
- Conduct Finite Element Analysis (FEA) of critical robot components under payload conditions.
- Evaluate stress distribution, deformation, and structural stiffness of the manipulator.
- Validate the kinematic and simulation results for manufacturing automation applications.
- Assess the suitability of the developed robotic manipulator for industrial tasks such as welding, material handling, and inspection.

4. Materials and Methedology

4.1 Robot Design Specifications

A six-degree-of-freedom (6-DOF) robotic manipulator prototype was developed to investigate the kinematic behaviour, workspace characteristics, and motion control of robotic systems for manufacturing automation. The prototype consists of six revolute joints driven by servo motors, providing complete control over the position and orientation of the end-effector for pick-and-place and trajectory-following tasks.

The manipulator is controlled using a Raspberry Pi in combination with a PCA9685 servo driver for accurate joint actuation. The mechanical structure was designed in SolidWorks, while RoboDK was used for kinematic modelling, workspace analysis, and trajectory simulation. Dynamic performance, including joint motion and system behaviour, was evaluated using MSC ADAMS. This integrated design and simulation approach enabled comprehensive analysis of the manipulator before physical implementation.

4.2 CAD Modelling

The robotic manipulator was modelled using a three-dimensional parametric CAD approach. Individual components such as the base, links, joints, wrist assembly, and end-effector mounting bracket were designed and assembled to form the complete robotic system. The dimensions of each link were selected to achieve adequate workspace coverage while maintaining structural stability and ease of fabrication.

The developed CAD model was imported into RoboDK for kinematic analysis, workspace evaluation, and trajectory simulation. Dynamic analysis was subsequently performed using MSC ADAMS to estimate joint torque requirements under different operating conditions. The finalized design was fabricated using additive manufacturing techniques and integrated with servo motors, Raspberry Pi, and PCA9685 controller hardware to develop a functional robotic manipulator prototype for experimental validation.

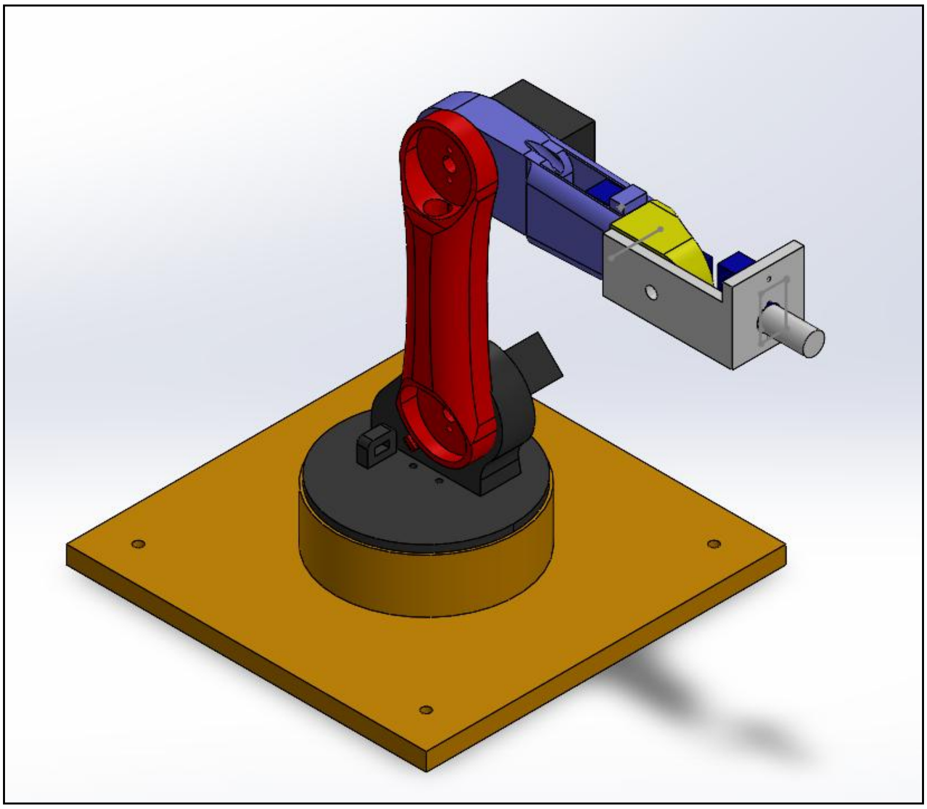

Figure 1: 3D CAD model of robot arm

4.3 Kinematic Modelling

The kinematic model of the robotic manipulator was developed using the Denavit–Hartenberg (D-H) convention. Each joint and link was assigned a local coordinate frame, and the corresponding D-H parameters were defined to establish the mathematical relationship between joint variables and end-effector position. Forward kinematic equations were formulated to determine the position and orientation of the end-effector for a given set of joint angles, while inverse kinematic analysis was performed to calculate the required joint variables for a desired end-effector location. The kinematic model was subsequently validated through simulation studies.

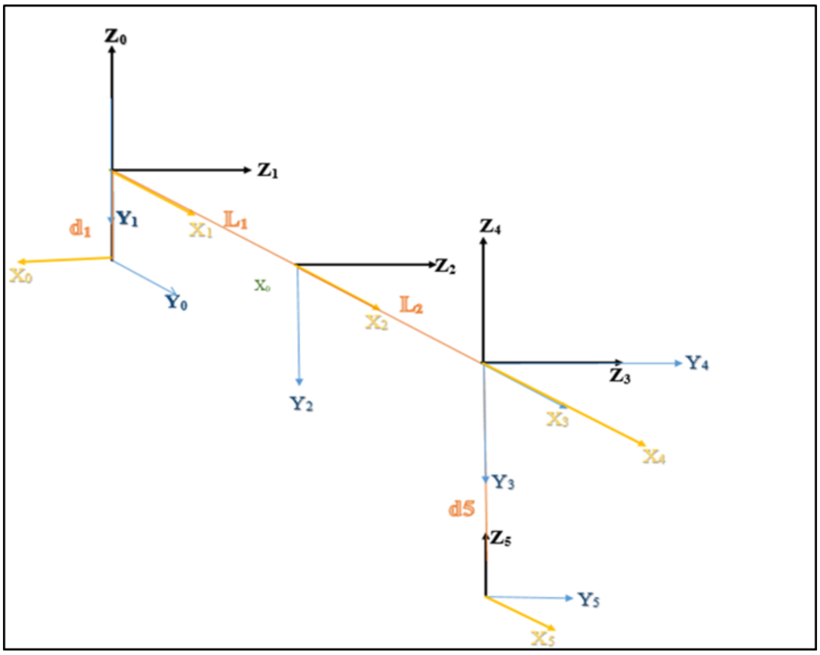

Figure 2: Kinematic Configuration of the Manipulator

Table 4.2: DH parameter of the 6-DOF configuration

θ_i	d_i	a_i	α_i
θ_1	d_1	a_1	-90
θ_2	0	a_2	0
θ_3	0	0	-90
θ_4	d_4	0	90
θ_5	0	0	-90
θ_6	d_6	0	0

4.4 RoboDK Simulation and Workspace Analysis

The developed CAD model was imported into RoboDK to evaluate the operational performance of the manipulator. Simulation studies were conducted to verify robot motion, trajectory execution, and workspace accessibility. Various target positions were defined within the workspace, and collision-free motion planning was performed to ensure smooth end-effector movement. Reachability analysis confirmed that the manipulator could successfully access the desired working region while maintaining adequate orientation control. The simulation environment also enabled visualization of robot trajectories before physical implementation.

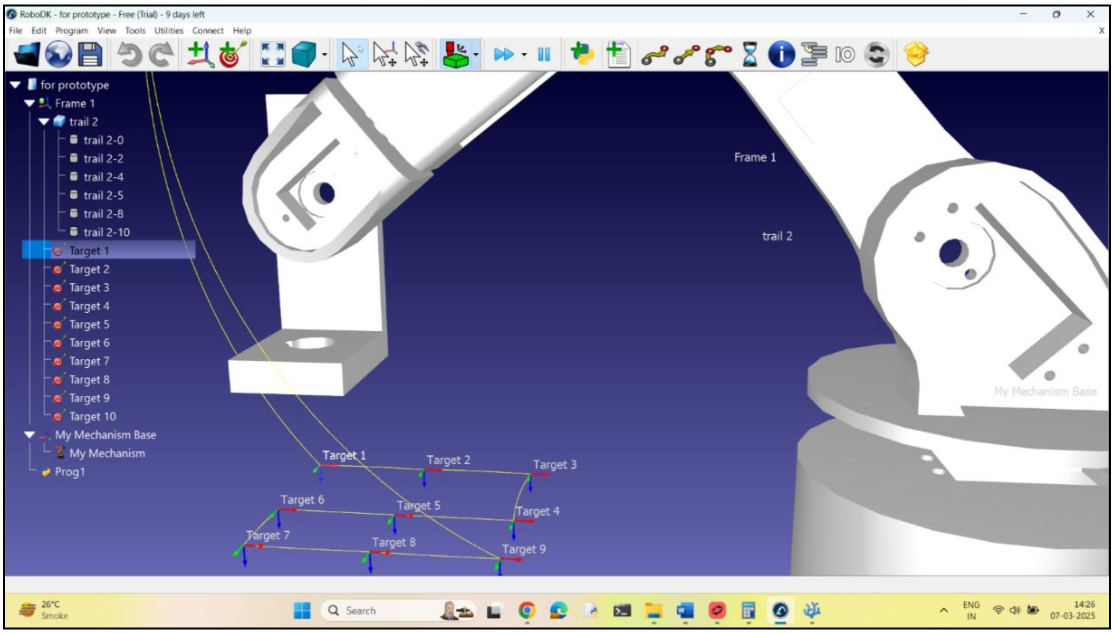

Figure 3: RoboDK Trajectory execution

4.5 Dynamic Analysis Using MSC ADAMS

Dynamic analysis of the robotic manipulator was carried out using MSC ADAMS to estimate the torque requirements of individual joints during operation. The CAD assembly was imported into the ADAMS environment, where revolute joints and motion inputs were defined according to the manipulator configuration. Simulations were performed under representative operating conditions to determine joint displacement, velocity, acceleration, and torque characteristics.

The analysis identified the critical loading conditions experienced by the manipulator and provided valuable information for actuator selection. Torque profiles obtained from the simulation indicated that the base and shoulder joints experienced higher loading compared to wrist joints due to their responsibility for supporting the weight of subsequent links. The dynamic analysis validated the feasibility of the proposed design and provided a basis for selecting appropriate servo actuators for prototype development.

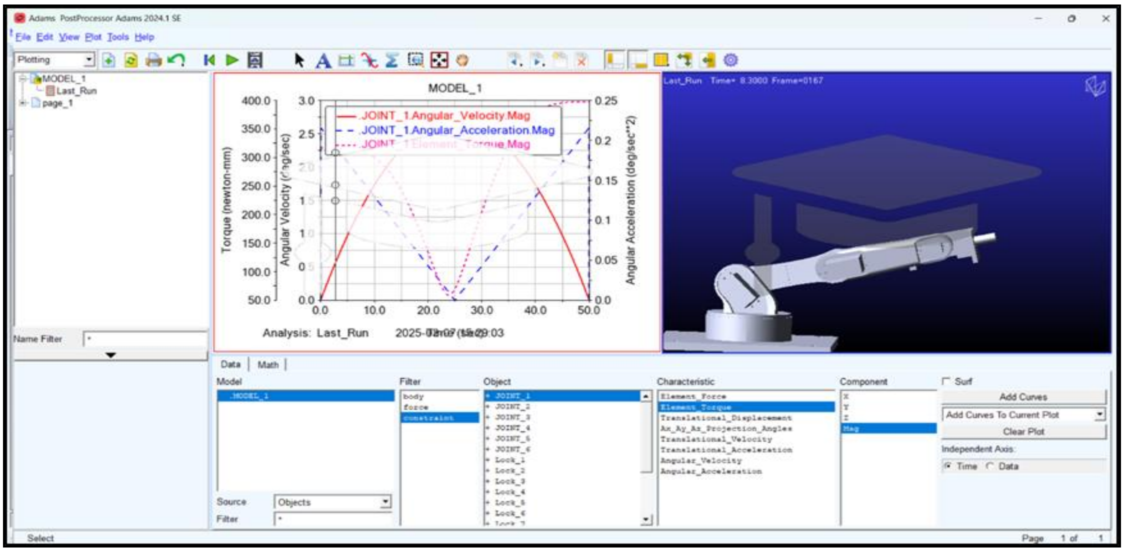

Figure 4. Snap of ADAMS Interface

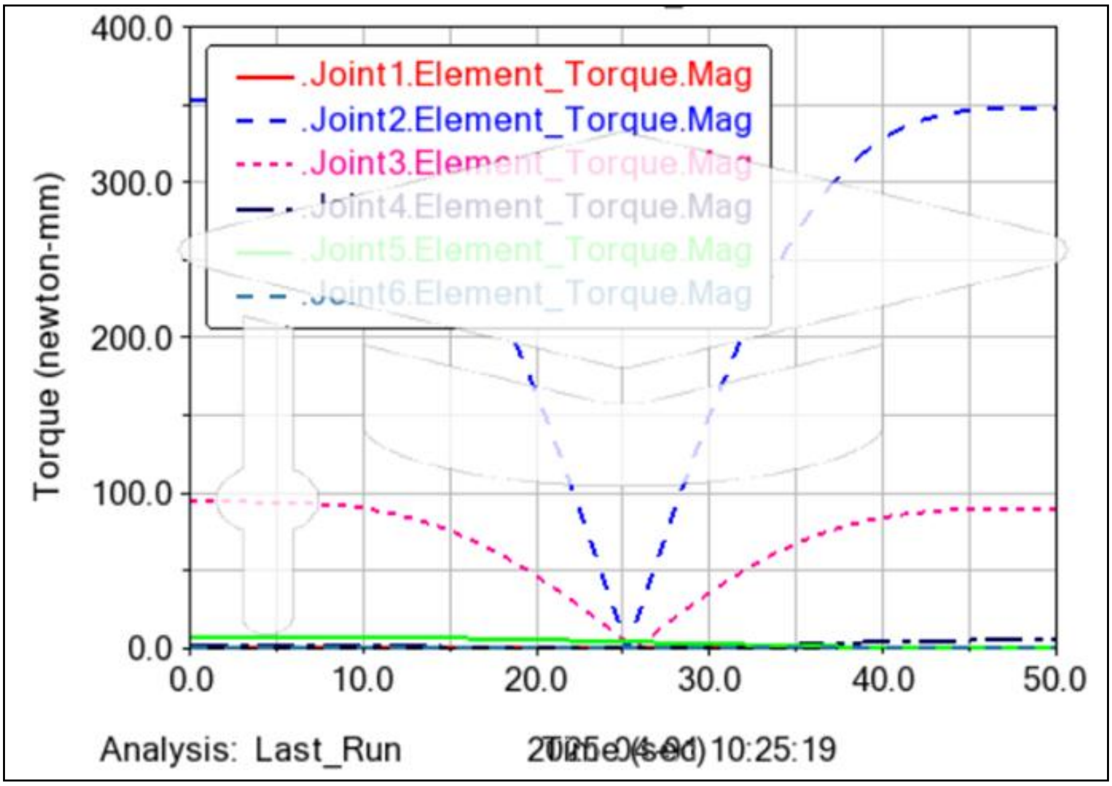

Figure 5. Torque profile for all 6 joints

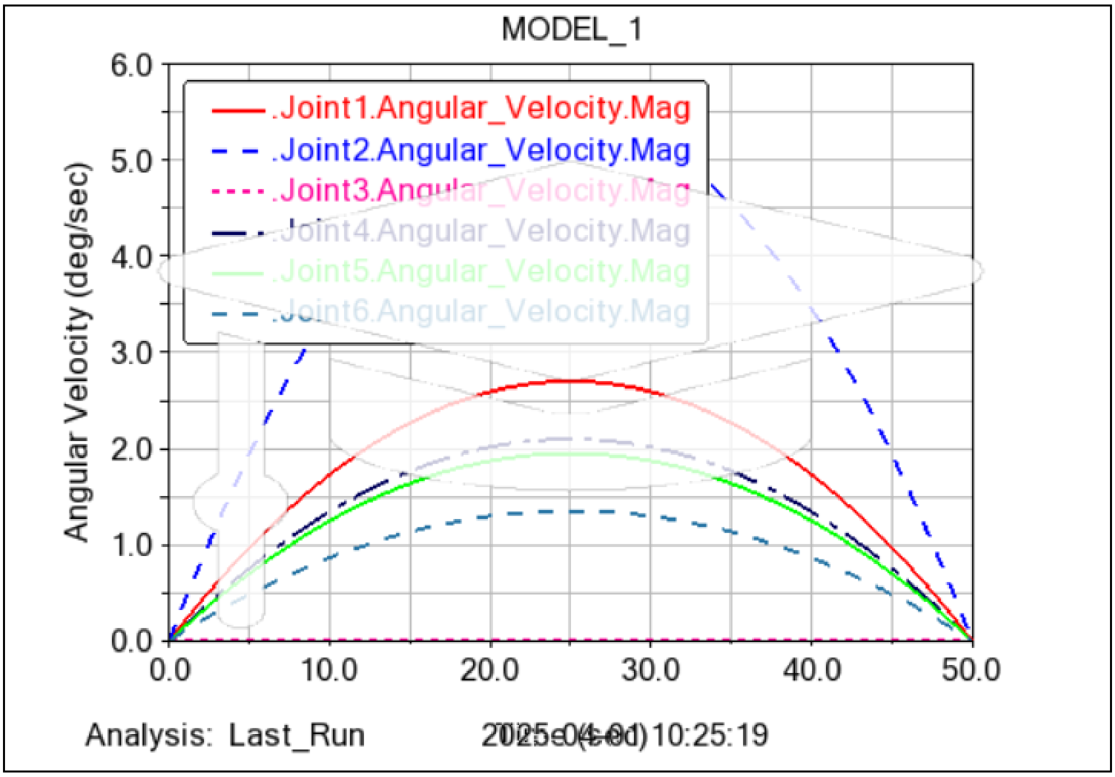

Figure 6. Velocity profile for all 6 joints

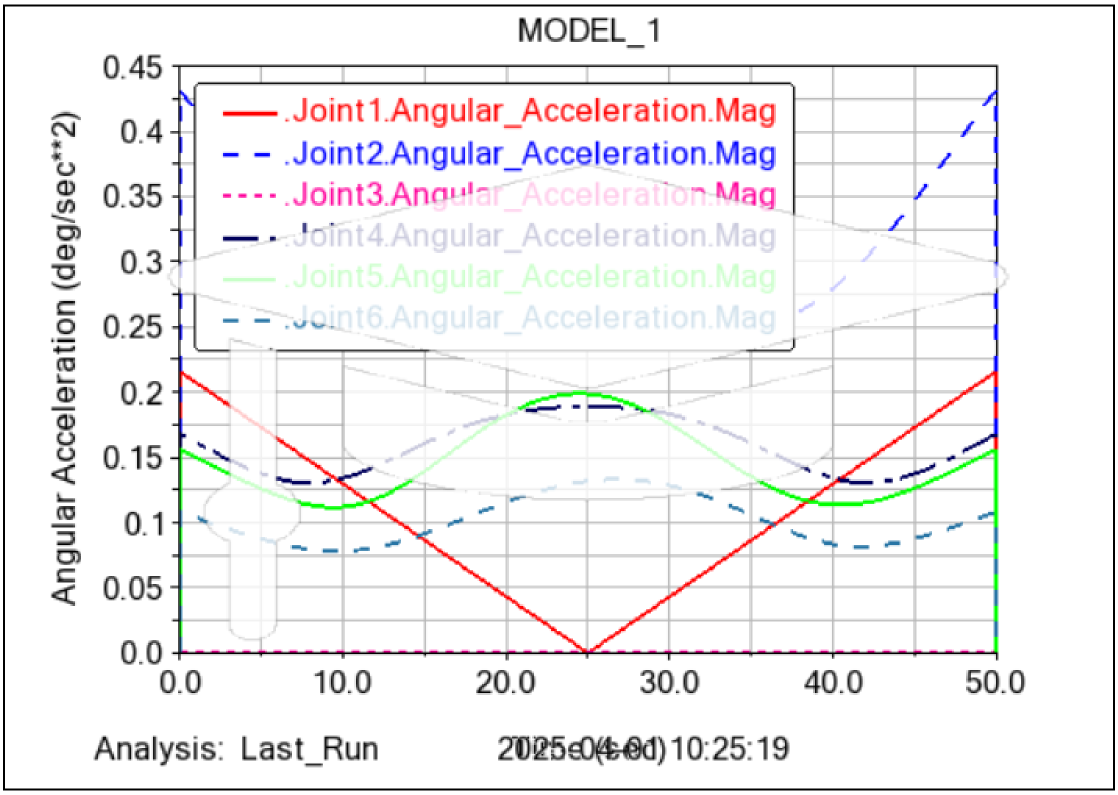

Figure 7. Acceleration profile for all 6 joints

4.6 Prototype Development and Hardware Integration

Following simulation and analysis, a physical prototype of the robotic manipulator was fabricated using additive manufacturing techniques. Servo motors were integrated with the mechanical structure to provide actuation for all six joints. The control system consisted of a Raspberry Pi and PCA9685 servo driver module, enabling coordinated joint movement and real-time trajectory execution. Experimental testing was performed to validate the functionality of the manipulator and compare physical motion with simulation results.

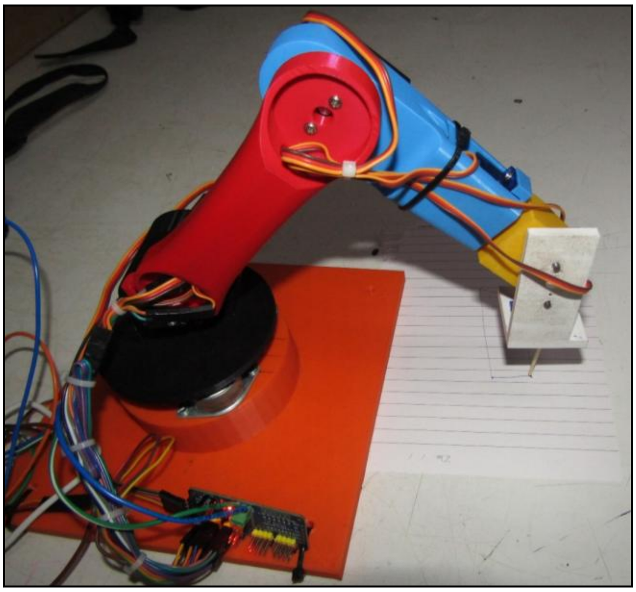

Figure 8: Fabricated 6-DOF Robotic Manipulator Prototype

5. Results and Discussion

The developed 6-DOF robotic manipulator was successfully modelled, simulated, and experimentally validated for manufacturing automation applications. The CAD model was created using SolidWorks and subsequently imported into RoboDK and MSC ADAMS for kinematic and dynamic analysis.

The Denavit-Hartenberg (D-H) method was employed to establish the kinematic model of the manipulator. Forward kinematic analysis demonstrated that the end-effector position and orientation could be accurately determined for different joint configurations. The kinematic model provided the foundation for workspace analysis and trajectory planning, ensuring smooth and coordinated motion of all six joints.

Simulation studies performed in RoboDK verified the operational capabilities of the robotic manipulator. Various target positions were defined within the workspace, and the manipulator successfully executed the required motion trajectories without encountering kinematic singularities or joint limit violations. The simulation results confirmed that the selected link dimensions and joint arrangement provide adequate workspace coverage for typical manufacturing automation tasks.

Dynamic analysis was carried out using MSC ADAMS to evaluate the motion characteristics and actuator requirements of the robotic manipulator. The analysis revealed that the base and shoulder joints experienced the highest torque requirements due to the cumulative weight of subsequent links and actuators. In contrast, the wrist joints required comparatively lower torque because of their smaller load contribution. The obtained torque profiles were utilized for selecting suitable servo motors and validating the mechanical design.

A physical prototype of the manipulator was fabricated using additive manufacturing techniques and integrated with servo motors, Raspberry Pi, and a PCA9685 servo controller. Experimental testing demonstrated successful execution of programmed joint movements and trajectory-following operations. The manipulator exhibited stable operation and satisfactory positioning performance during repeated motion cycles.

Comparison between simulation and experimental observations showed good agreement in terms of motion behaviour and workspace accessibility. Minor deviations were observed due to manufacturing tolerances, servo backlash, and assembly inaccuracies. However, these variations did not significantly affect the overall functionality of the system. The results confirm that the proposed design methodology is suitable for the development of low-cost robotic manipulators intended for educational, research, and light industrial automation applications.

6. Conclusions

This research presented the design, modelling, simulation, and prototype development of a 6-DOF robotic manipulator for manufacturing automation applications. A complete CAD model was developed and analysed using kinematic and dynamic simulation tools to evaluate the operational performance of the system.

The Denavit-Hartenberg based kinematic model successfully determined the end-effector position and orientation for various joint configurations. RoboDK simulation verified the workspace coverage and trajectory execution capabilities of the manipulator, while MSC ADAMS analysis provided valuable insights into joint motion characteristics and actuator torque requirements.

The fabricated prototype demonstrated successful execution of programmed motions and validated the simulation results. Experimental testing confirmed that the developed manipulator is capable of performing basic automation tasks with satisfactory accuracy and repeatability. The good correlation between simulation and physical implementation validates the effectiveness of the adopted design methodology.

Overall, the study demonstrates the feasibility of developing a compact and cost-effective 6-DOF robotic manipulator using commercially available components and simulation-driven design techniques. The developed system provides a strong foundation for future work involving machine vision integration, intelligent path planning, advanced control strategies, and industrial automation applications.

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