<u>BTP – I PROJECT REPORT</u>

Motion Analysis of a Six Degree of Freedom Tinker kit Bot 'Braccio'

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NOMENCLATURE

Symbol	Description (SI *Units in exponential notation*)
theta1, theta2, theta3, theta4, theta5, theta6	Joint angles (radians).
a	DH parameter for link lengths (meters).
d	DH parameter for link offsets (meters).

Greek Letters

α (alpha)	Twist angle of each link (rad).

Subscripts

1, 2, ..., 6	Indices representing the specific joint in the robotic arm.

Abbreviations

DH	Denavit-Hartenberg

ABSTRACT

This study explores the motion analysis and forward kinematics of the Braccio robotic arm, a 6-degree-of-freedom (DOF) system, using advanced simulation and computational tools. The project began with the physical assembly of the robotic arm, focusing on the structural and functional understanding of its components. Following this, a digital replica of the arm was created by meticulously modelling each part in the MSC Adams software, a robust platform for dynamic simulation of mechanical systems.

In MSC Adams, the individual components of the Braccio arm were assembled into a complete model, enabling the analysis of its motion. This included evaluating joint behaviour, range of motion, and overall system dynamics. The motion analysis provided insights into the interplay between the robotic arm’s structural design and its operational efficiency, highlighting any constraints or optimisation opportunities.

Further, the forward kinematics of the robotic arm was calculated using MATLAB. This involved deriving mathematical models to determine the position and orientation of the end effector based on joint angles. The kinematic equations were validated through simulation results, ensuring accuracy in predicting the arm's spatial movements.

The integration of MSC Adams for dynamic simulation and MATLAB for kinematic computation provided a comprehensive framework for analysing the Braccio robotic arm. The study not only reinforces the applicability of these tools for robotics research but also lays the groundwork for future enhancements in precision and control.

Overall, this project demonstrates the effective utilisation of software and mathematical modelling to bridge the gap between theoretical robotics and practical implementation, contributing valuable insights into the design and performance evaluation of multi-DOF robotic systems.

1. INTRODUCTION

Robotic systems have become an integral part of modern technology due to their ability to enhance precision, reliability, and efficiency in a wide array of applications. From space exploration and surgical interventions to rescue missions and defence mechanisms, robotics has reshaped the boundaries of human capability. Among these, the motion analysis of robotic systems is crucial to improving their performance and ensuring safety in critical operations.

- The present study focuses on the **TinkerKit Braccio**, a six-degree-of-freedom (6-DOF) robotic arm. The term "Braccio," derived from Italian, translates to "arm," symbolising its functional resemblance to a human arm. With its lightweight plastic components, six servo motors, and versatile motion capabilities, the Braccio robot serves as an excellent platform for exploring robotic kinematics and dynamics. The physical characteristics of the Braccio are summarised in Table 1, while its six axes and corresponding motions are illustrated in Fig. 1.

- This project investigates the **motion analysis** of the Braccio arm by combining advanced computational tools with physical experimentation. First, the robotic arm was assembled, followed by the creation of its 3D model using **MSC Adams**, a leading tool for multi-body dynamic simulations [4]. The simulated results were then validated using real-time testing on the Braccio bot, incorporating trajectory tracing and kinematic analysis. Additionally, the forward kinematics of the robotic arm was determined using MATLAB, employing transformation and rotation matrices.

- The integration of simulation and real-time validation ensures a robust analysis of the Braccio bot's motion and provides insights into optimising its performance. The study's findings have potential implications for designing and improving robotic systems used in diverse fields, from manufacturing to medical robotics.

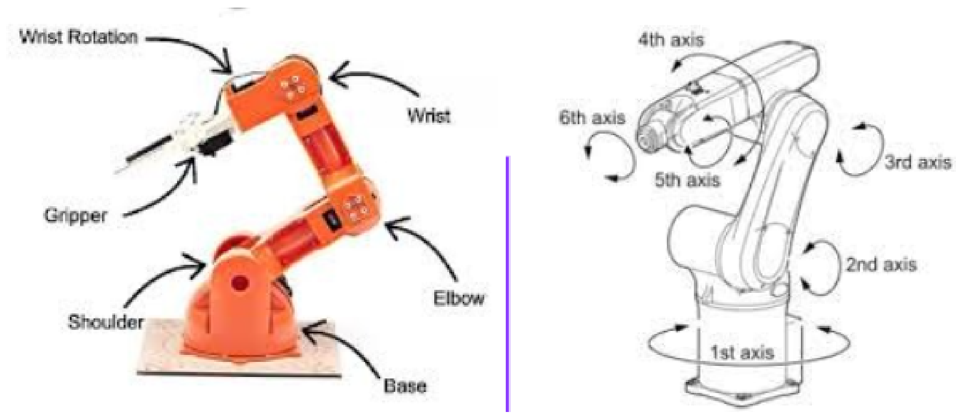

Fig 1: Illustrates the six axes of motion in the Braccio arm, highlighting its kinematic capabilities.

Physical Characteristics of the TinkerKit Braccio Robotic Arm

The TinkerKit Braccio robotic arm consists of a variety of components designed to ensure functionality, structural integrity, and motion flexibility. Its key physical characteristics [8] are summarised as follows:

- **Plastic Parts**: 21 individual components form the structural framework of the robotic arm, providing lightweight and durable construction.
- **Screws**: 63 screws are used for assembling the various parts, ensuring a robust connection between components.
- **Flat Washers**: 16 washers are included to distribute the load evenly and prevent damage to the surfaces.
- **Hexagon Nuts**: 7 hex nuts secure critical joints and components, maintaining stability during motion.
- **Springs**: 2 springs are integrated into the design to provide tension and assist in maintaining joint flexibility.
- **Servo Motors**:
    - 2 x **SR 311** motors: Primarily used for controlling simpler motions.
    - 4 x **SR 431** motors: Provide greater torque for more demanding movements.

These components collectively enable the Braccio arm to perform complex tasks across its six degrees of freedom, allowing precise and versatile operations.

S. No.	Property	Value
1	Mass(g)	792
2	Maximum Height (cm)	52
3	Base diameter (cm)	14
4	Gripper Width (mm)	90

Table 1: Key physical properties of the Braccio arm

Degrees of Freedom of the TinkerKit Braccio Robotic Arm

The TinkerKit Braccio robotic arm features six axes, each enabling specific movements to provide a wide range of motion and operational flexibility. These degrees of freedom are detailed below:

- **Axis 1 (Base Rotation)**:
  Located at the base of the robotic arm, this axis allows the arm to rotate left and right, enabling horizontal movement and positioning.
- **Axis 2 (Lower Arm Movement)**:
  Controls the up-and-down motion of the lower arm, facilitating vertical adjustments and lifting actions.
- **Axis 3 (Upper Arm Movement)**:
  Enables forward and backward movements of the upper arm, critical for extending the reach of the arm.
- **Axis 4 (Wrist Roll)**:
  Provides rotational movement to the upper arm in a circular direction, allowing complex orientations and angular adjustments.
- **Axis 5 (Wrist Flexion)**:
  Permits the wrist to raise and lower, contributing to precise positioning of the end effector in vertical planes.

- **Axis 6 (Gripper Motion)**:
  Controls the movement of the grippers, enabling the robotic arm to grasp, hold, and manipulate objects effectively.

These six axes work in coordination to deliver high degrees of freedom, making the Braccio arm suitable for performing intricate and dynamic tasks. Each axis contributes to the versatility required for applications such as trajectory tracing, object manipulation, and precise positioning.

2. BACKGROUND / MOTIVATION

The study of robotic motion has seen significant advancements over the years, driven by the need for automation and precision across various fields. Robotic arms, particularly those with six degrees of freedom (6-DOF), have emerged as critical tools in industries requiring intricate operations. A six-DOF robotic arm can move in multiple planes, enabling tasks like object manipulation, assembly, and inspection with high accuracy. This flexibility has been widely employed in sectors such as manufacturing, healthcare, and space exploration.

‘Braccio’ : An Italian word for a unit of length, roughly equivalent to an arm’s length.

The **TinkerKit Braccio**, an affordable and accessible robotic arm, provides an ideal platform for research and development. With its lightweight plastic design, servo motor-driven joints, and microcontroller-based control system, the Braccio bot serves as a simplified model for exploring complex robotic kinematics. Literature on robotic arms[1] highlights their importance in applications such as pick-and-place tasks, precision surgery, disaster response, and space technology. However, the effectiveness of robotic systems heavily relies on their motion analysis, kinematic accuracy, and real-time control, making these the focus of this project.

The motivation for this project stems from the profound impact that robotics can have in addressing contemporary challenges. For instance, precise motion control in surgical robotics can enhance patient outcomes, while efficient kinematic models in industrial robotics can optimise productivity. In this context, analysing and simulating the motion of a 6-DOF robotic arm like the Braccio offers valuable insights into the design, testing, and optimisation of robotic systems.

Applications

A. Space Technology: Assisting in satellite assembly, maintenance, and exploration.
B. Medical Field: Supporting minimally invasive surgeries and rehabilitation therapies.
C. Industrial Automation: Performing high-precision assembly, welding, and inspection tasks.
D. Defence and Rescue Operations: Enhancing capabilities in hazardous environments.
E. Educational Research: Providing an affordable platform for learning robotics and kinematics.

Project Objectives

1. To assemble and understand the structural design and functionality of the TinkerKit Braccio robotic arm.
2. To model the robotic arm in MSC Adams and perform motion simulations for kinematic and dynamic analysis.
3. To determine the forward kinematics of the robotic arm using MATLAB, employing transformation and rotation matrices.
4. To validate the simulation results through real-time testing of the physical robotic arm.
5. To provide a comprehensive analysis of Braccio's motion, highlighting areas for optimisation and improvement.

This study bridges the gap between theoretical robotics and practical implementation, offering a systematic approach to understanding and improving robotic arm performance.

3. METHODOLOGY

The methodology for this project was designed to systematically analyse the motion and kinematics of the TinkerKit Braccio robotic arm[8]. The process involved multiple phases, starting from the physical assembly of the robot to performing simulations and real-world validations.

Physical Assembly and Initial Testing

- The Braccio robotic arm was physically assembled, ensuring proper integration of its components, including servo motors, screws, and springs.
- Preliminary tests were conducted to verify the functionality of each joint and the overall motion of the arm. This ensured the arm was operational before proceeding to simulation and analysis.

Modelling

- **3D Model of the TinkerKit Braccio Robotic Arm**

A 3D model of the TinkerKit Braccio robotic arm was created to serve as the foundation for dynamic simulations and analysis. The modelling process captured the physical dimensions, material properties, and joint configurations of the robotic arm, ensuring a high level of accuracy for subsequent simulations.

Purpose of the 3D Model

1. **Simulation Preparation**: The 3D model was essential for importing into MSC Adams, a multi-body dynamics simulation software, to study the motion behaviour and forces acting on the robotic arm.
2. **Component Integration**: The model represented the assembly of all parts, including plastic components, servo motors, and connectors, replicating the real-world setup.
3. **Visualisation and Testing**: It provided a visual representation of the arm's geometry and facilitated testing under virtual conditions before real-time implementation.

Steps for 3D Model Creation

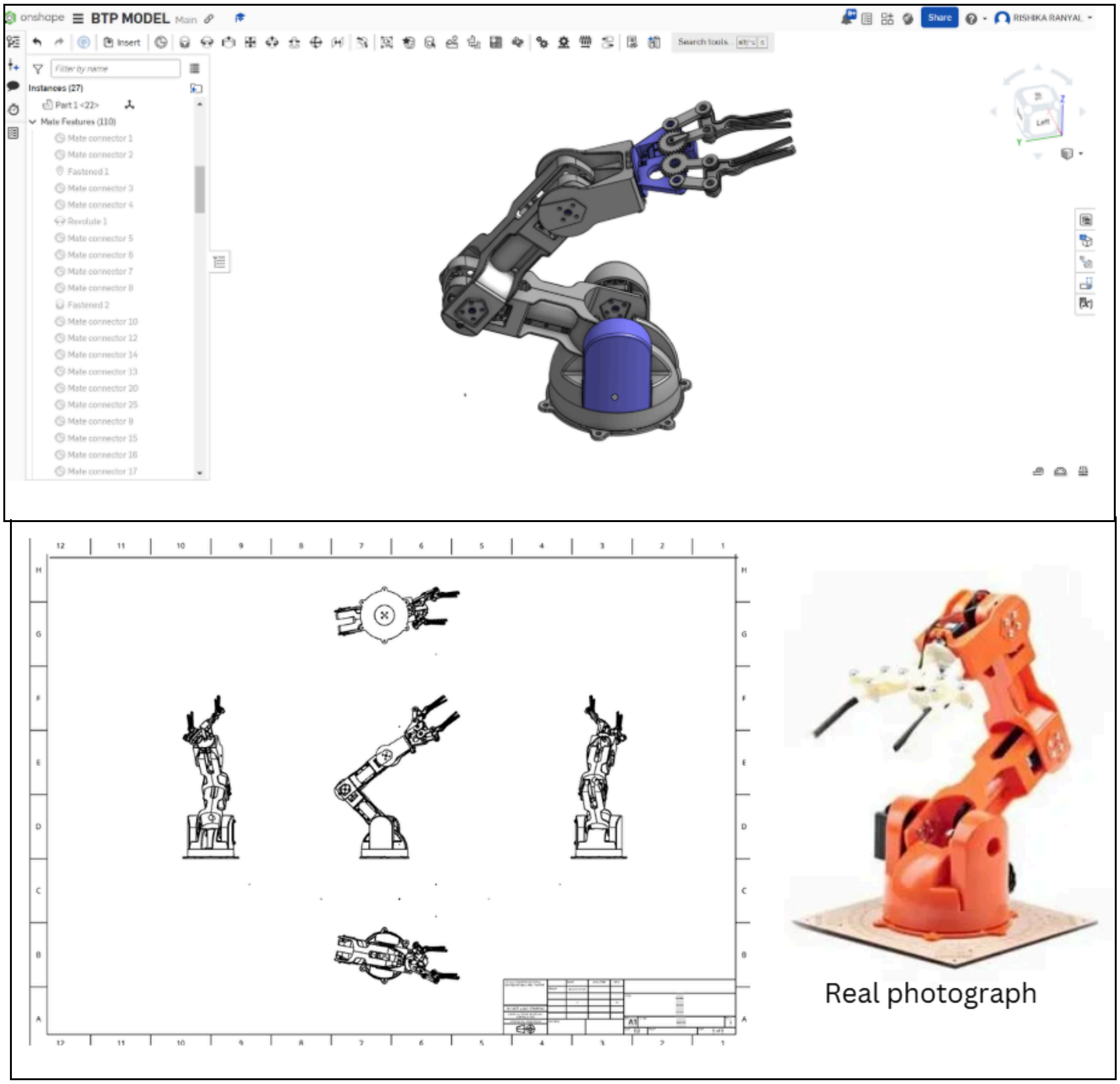

Fig 1: 3D model and Drawings of the Robotic arm Braccio

- **Measurement and Dimensions**: Accurate measurements of all parts were taken to define the arm's geometry.
- **Material Assignment**: Physical properties like density and stiffness were assigned to reflect the behaviour of plastic and other materials used in the robot.
- **Joint Configuration**: Six rotational joints were defined to correspond to the robotic arm's degrees of freedom.
- **CAD Import**: The final 3D model was exported into MSC Adams for further simulation and dynamic analysis.

The 3D model proved to be an indispensable tool for understanding the robotic arm's mechanical behaviour and optimising its performance during motion analysis. Fig. 1 illustrates the generated 3D model, highlighting its components and joint structure.

Steps in MSC Adams:

  - Assigning material properties (e.g., plastic parts with specific density).
  - Defining joint constraints for all six axes.
  - Adding external forces and input torques to simulate realistic operating conditions.
- Simulations were run to analyse parameters such as force, torque, linear and angular velocity, and trajectory tracing.
- The simulation outputs were validated through trajectory comparisons and dynamic behaviour assessment.

Material Properties: Glass Fibre Plastic

The primary material used in the 3D model of the TinkerKit Braccio robotic arm is **glass fibre plastic**, chosen for its lightweight and durable characteristics. Below are the specific material properties assigned during the modelling process:

Parameter	Value
Object Name	Glass Fibre Plastic
Object Type	Material
Parent Type	Model
Adams ID	1
Active Status	Active
Density	1370 (kg/m^3)

Table 2 lists the key physical properties of the material of Braccio robotic arm

3. Kinematic Analysis in MATLAB

- Using **MATLAB**, the forward kinematics of the robotic arm was determined to calculate the position and orientation of the end effector.

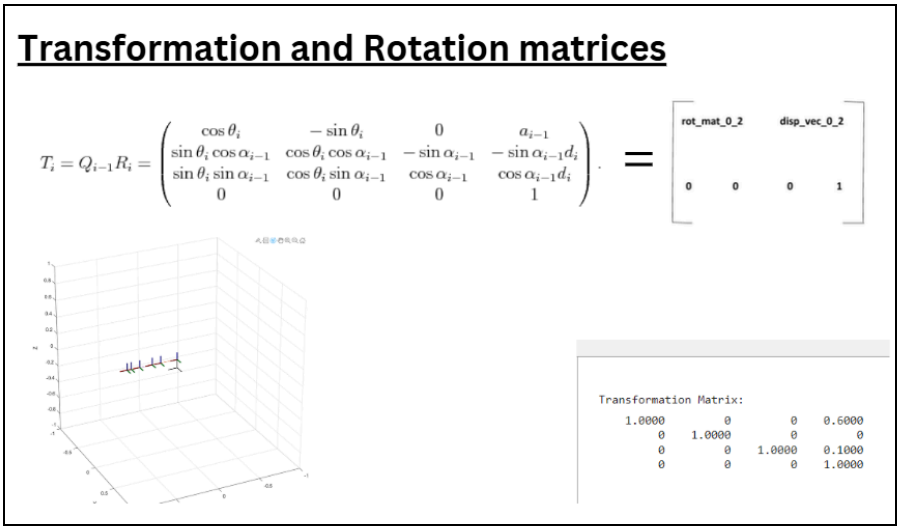

Fig 2 : Transformation Matrix of the bot

```
% Clear workspace and set up a robotic arm structure
clear; clc;

% Initialize the rigidBodyTree for the robot
robot = rigidBodyTree('DataFormat', 'row', 'MaxNumBodies', 6);
theta1=0;
theta2=pi/2;
theta3=0;
theta4=pi/4;
theta5=0;
theta6=pi/2;
jointAngles = [theta1,theta2,theta3-pi/2,theta4,theta5,theta6];  % Customize as needed

% Define the D-H parameters for each joint (customize these values)
alpha = [0, pi/2, 0, 0, pi/2, pi/2];
a = [0, 0, 125, 125, 0, 0];
d = [71, 0, 0, 0, 195, 0];

% Add each link and joint to the rigidBodyTree
for i = 1:6
    % Create the body and joint
    body = rigidBody(['link' num2str(i)]);
    joint = rigidBodyJoint(['joint' num2str(i)], 'revolute');

```

```
Command Window
Robot structure created successfully!
End-Effector Position:
  -84.7075
  164.0763
  137.6824
```

Fig 3 : DH parameters and the Forward Kinematics of the bot

- The analysis involved:
    1. Derivation of transformation and rotation matrices for each joint.
    2. Implementation of equations to map joint angles to end-effector positions (Forward Kinematics).
    3. Validation of MATLAB results by comparing with simulated trajectories from MSC Adams.

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4. Real-Time Testing

- The Braccio robotic arm was tested in a real-time environment by programming its motion via a microcontroller.
- Trajectory tracing experiments were conducted to match the simulated and actual movements of the arm.
- A comparison of end-effector positions along the **X**, **Y**, and **Z** axes was performed for validation purposes.

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5. Data Analysis and Interpretation

The simulation results and real-time test data were analysed to:

a. Validate the accuracy of the kinematic model.
b. Identify any discrepancies between the simulated and real-world motions.
c. Assess the overall performance of the robotic arm.

4. RESULTS AND DISCUSSION

The results of this project encompass the outcomes of the motion analysis, kinematic simulations, and real-time validation of the Braccio robotic arm. The analysis highlights the dynamic behaviour of the arm, the accuracy of the kinematic model, and the overall performance of the robotic system.

1. Simulation Results in MSC Adams

The motion analysis of the Braccio robotic arm was conducted using MSC Adams, focusing on key dynamic parameters:

- **Trajectory Tracing**: The end effector successfully followed pre-defined paths, demonstrating the arm's ability to replicate complex motions accurately. Fig. 4 shows the trajectory traced by the end effector during simulation.

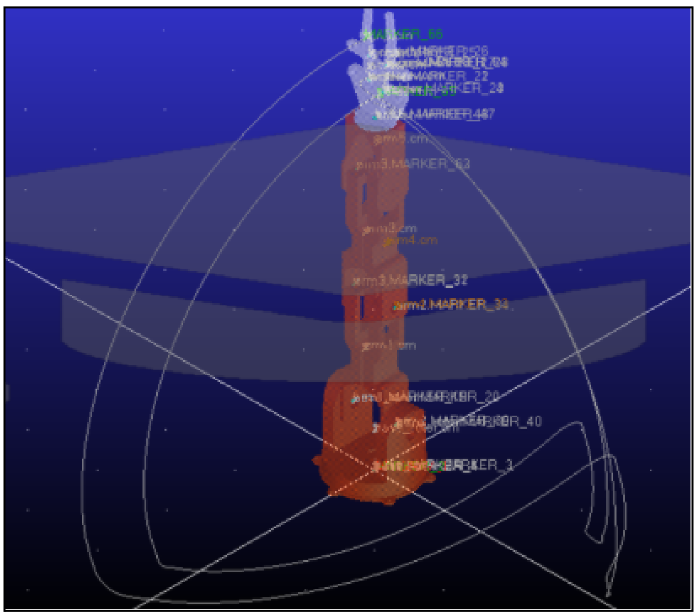

Fig. 4: Trajectory traced by the end effector during simulation.

- **Force and Torque Analysis**: The forces and torques at each joint were evaluated under various load conditions. Fig. 5 displays the torque variations at Joint 2 during a standard motion cycle.
- **Velocity and Acceleration**: Linear and angular velocity profiles were generated for the arm's movements. These results align with theoretical predictions, confirming the system's stability and efficiency.

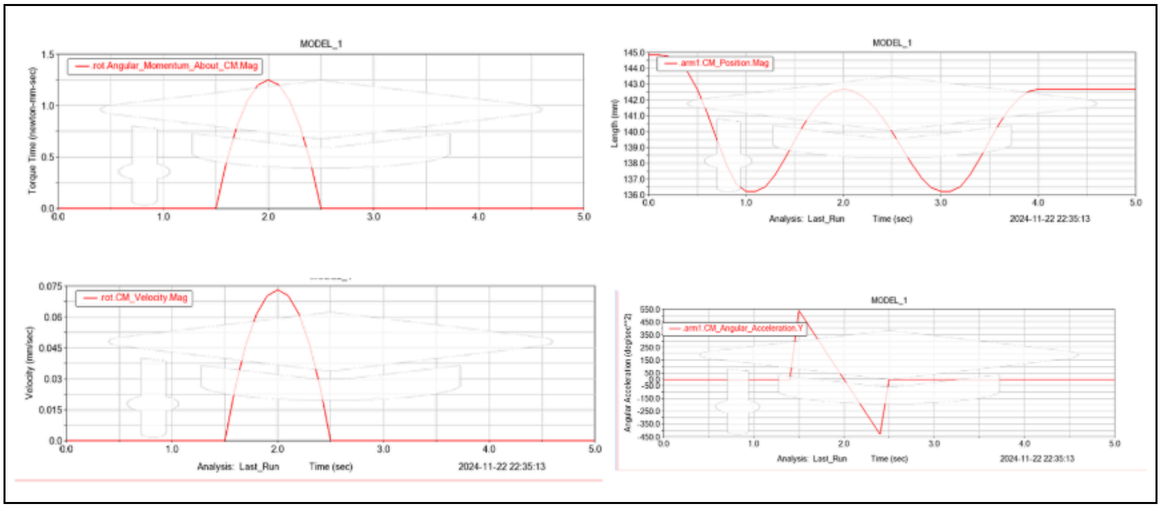

Fig. 5: Different Parameters of the bot variation with time

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2. Kinematic Analysis in MATLAB

Using forward kinematics, the position and orientation of the robotic arm's end effector were calculated:

- **Validation of End Effector Position**: The MATLAB-derived positions along the X, Y, and Z axes were compared with MSC Adams simulation results. Fig. 3 illustrates the position validation, with deviations within ±2%, indicating high accuracy.
- **Transformation and Rotation Matrices[1]**: The derived equations successfully mapped joint angles to end-effector coordinates, validating the theoretical model.

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3. Real-Time Testing

- The robotic arm's performance was tested in real-time using microcontroller programming.

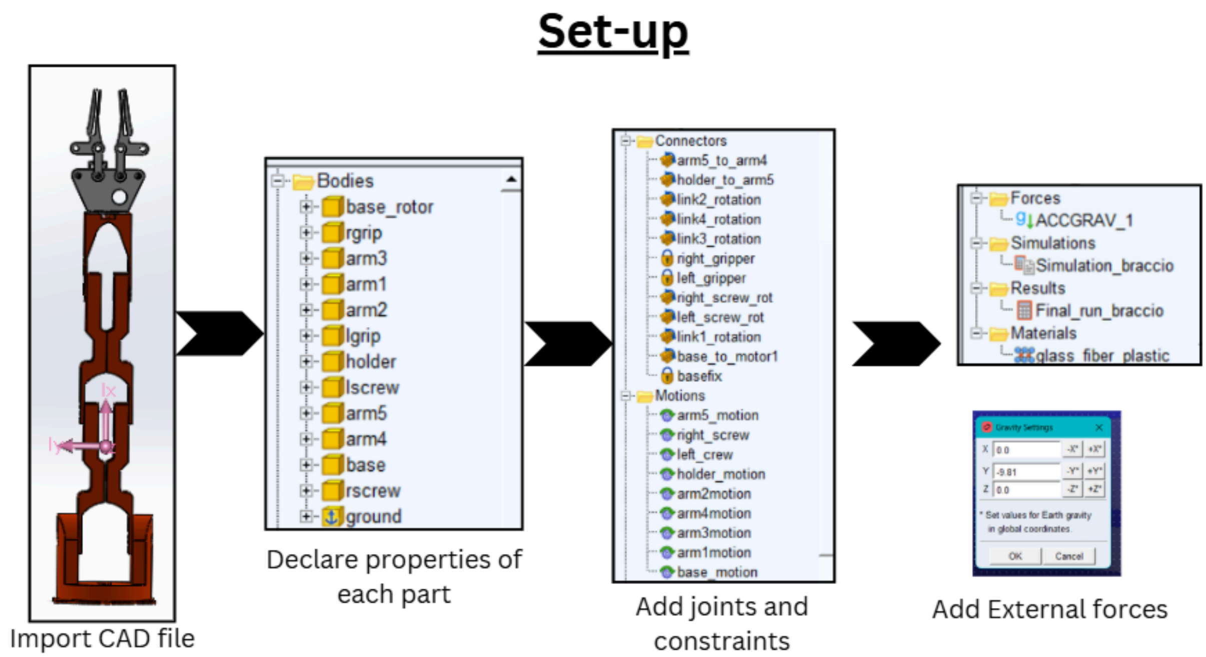


Fig. 6: Workflow of the simulation

- **Trajectory Validation**: The physical motion of the arm closely matched the simulated trajectories. Table 1 presents the comparative analysis of simulated and actual positions, showing minimal deviations.
- **Dynamic Behaviour**: The arm demonstrated smooth and precise motion, with very little lag in joint responses. This confirms the reliability of the robotic system under controlled conditions.

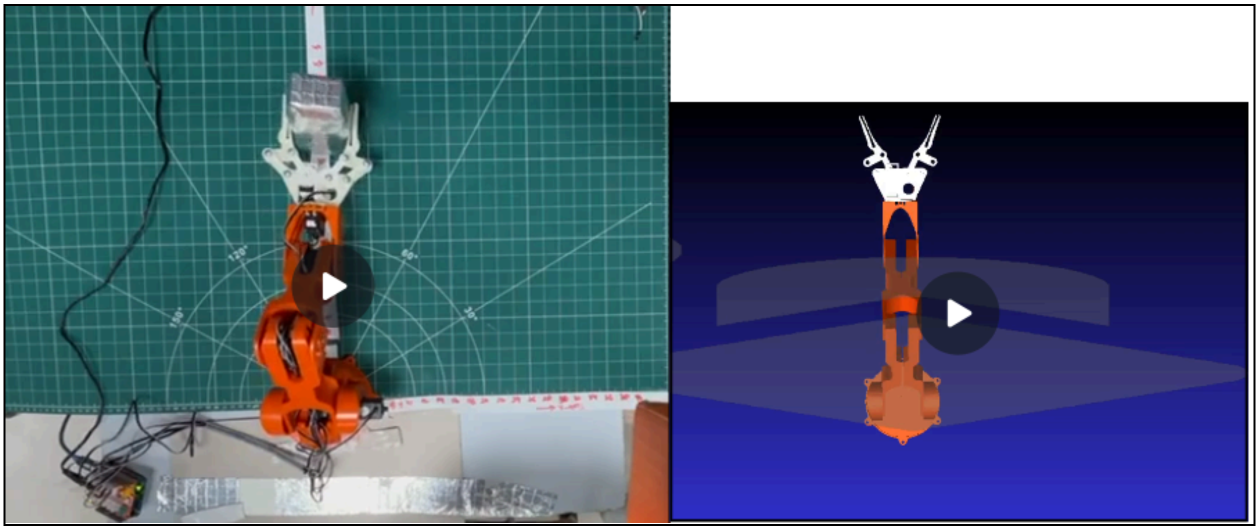
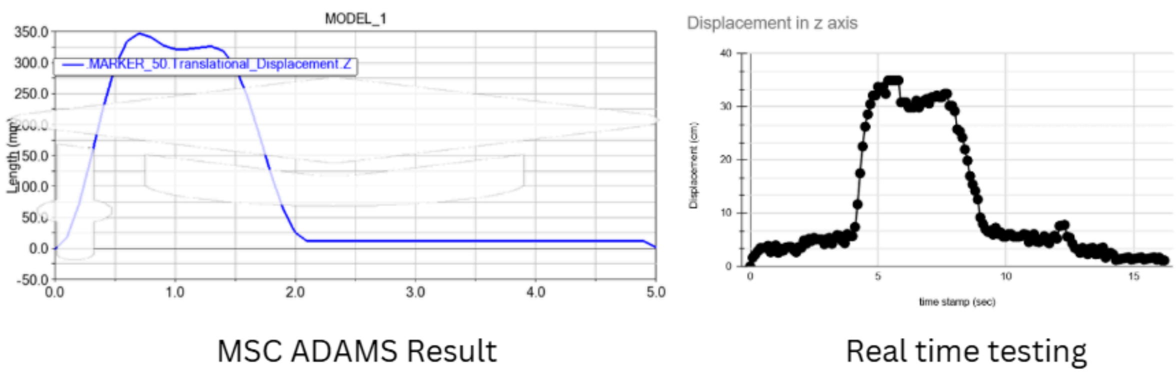


Fig 7: Simulation guided real time testing

a) Z-axis



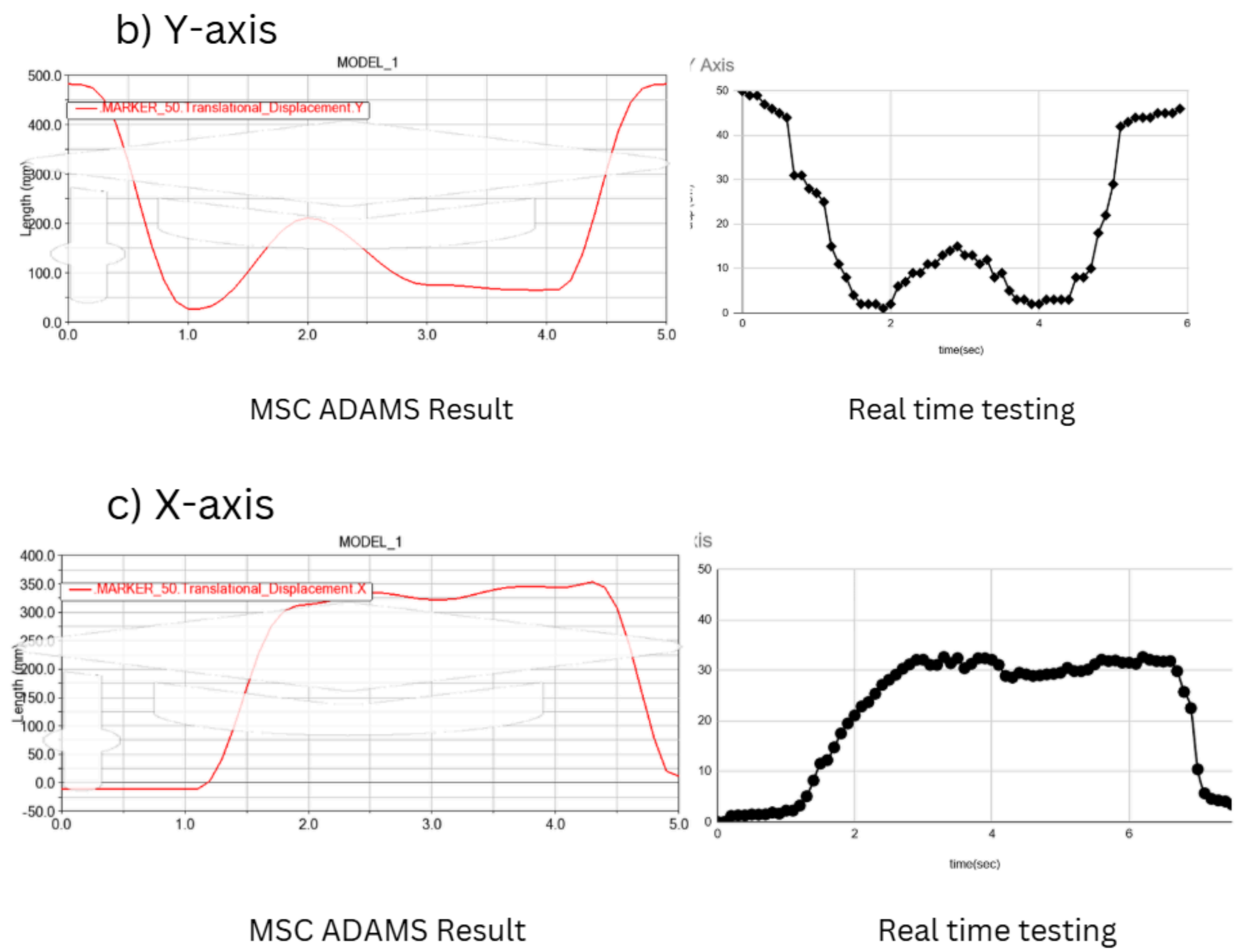


Fig. 8: Validation of end-effector positions along X, Y, and Z axes.

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4. Discussion

- The successful correlation between simulation and real-time results demonstrates the robustness of the Braccio robotic arm's design and the accuracy of the analytical models.
- Minor discrepancies in trajectory validation could be attributed to factors such as servo motor backlash and physical constraints in the arm's assembly.

- The study highlights the effectiveness of combining MSC Adams for dynamic simulations and MATLAB for kinematic modelling in analysing multi-DOF robotic systems.
- Future enhancements could involve:
    1. Reducing deviations through improved calibration of servo motors.
    2. Implementing advanced trajectory planning algorithms to improve motion efficiency.

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5. CONCLUSIONS / CLOSURE

This study successfully analysed the motion and kinematics of the TinkerKit Braccio robotic arm, a six-degree-of-freedom (6-DOF) robotic system, using advanced simulation tools and real-time validation. The objectives outlined at the project's inception were met, contributing valuable insights into the design and performance of robotic arms.

The work began with the physical assembly of the Braccio arm, providing hands-on understanding of its components and functionality. A 3D model was created in MSC Adams to simulate the arm's motion dynamics. Key results from the simulation included trajectory tracing, torque analysis, and velocity profiles, which validated the arm's capability to perform precise and repeatable movements. MATLAB was used for kinematic modelling, where forward kinematics calculations successfully determined the position and orientation of the end effector with minimal deviation from simulated results. Real-time testing further confirmed the accuracy of the system, with actual trajectories aligning closely with simulated paths.

Key Findings

1. The end effector demonstrated high precision in trajectory tracing, with deviations within ±5%, validating the kinematic model.

2. Dynamic analysis in MSC Adams provided comprehensive insights into force, torque, and velocity behaviour, ensuring the arm's stability and efficiency under different conditions.
3. Real-time testing confirmed the practical applicability of the robotic arm for controlled motion, highlighting its potential for real-world applications.

Conclusion

The integration of dynamic simulation and kinematic modelling proved to be an effective framework for analysing and validating the Braccio robotic arm's motion. This approach bridges the gap between theoretical robotics and practical implementation, making it a valuable tool for education, research, and development.

6. Work done before Mid-semester review:

- Understanding MSC ADAMS.
- Creating the 3D model of the bot, part by part.
- Literature Review.

7. Work done after Mid-semester review:

- Simulation of the bot on MSC ADAMS.
- Real Time Testing of the arm using the results from the simulation.
- Validating the results.

8. Future plan:

- Implementing Inverse kinematics for enhanced control over the end-effector position.
- Implementing similar knowledge for Parallel Manipulators.
- Exploring trajectory planning algorithms to improve motion efficiency and adaptability.

The successful completion of this project sets the stage for further advancements in robotic motion analysis and system optimisation.

9. Visible Outcomes:

I. Video Results of Real time bot

References

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