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Comparative Study of Polynomial Trajectory Planning Methods (Cubic Vs Quintic) for Robotic Manipulators with Smoothness and Energy Considerations

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Abstract: Trajectory planning has been an important part of motion control of the robotic manipulators, as it directly impacts their smoothness, accuracy, and energy consumption. Continuous, dynamically feasible, and energy-efficient joint trajectories are essential in such cases as pick-and-place, welding, and assembly where the robots are operating at a high speed. Polynomial trajectory planning, in particular quintic and cubic polynomials has evolved to be a popular technique of trajectory generation, owing to its simplicity and ability to address the boundary conditions. In this paper, a comparative analysis of cubic and quintic polynomial trajectories of robotic manipulators is given with special emphasis on motion smoothness, jerk reduction, and energy expenditure. In order to explain and make a comparison both analytically and by simulation, a simple two-link (2R) manipulator model is selected. Analysis is carried out on both trajectories by having the same conditions on the boundaries and then MATLAB simulations are used to show the changes of the position, velocity, acceleration, and jerk. The resultant performance of cubic trajectories reflecting low computation costs implies discontinuity in acceleration and jerk, hence reduced fluid motion and increased energy demands on short time intervals. Conversely, quintic curves also provide continuous acceleration and velocity with close to zero endpoint jerk, and consequently, allow even smoother and efficient motion. The major conclusions of the research are as follows: cubic polynomies are suitable at slow speed or simple operations, and quintic polynomials trajectories are selected when working with precision-based and high-speed robots, where the smoothness and energy-saving are essential. ***Keywords- Trajectory planning, robotic manipulators, cubic polynomial, quintic polynomial, motion.***

I. INTRODUCTION

From simple pick-and-place operations, robotics has progressed to the level of intelligent manipulators with multi- degree-of-freedom that can perform exact and intricate tasks. The use of robots in factory production lines where speed and accuracy are keener requires smooth and energy-efficient motion to be the winning point. The motion of the robot is dynamically planned with the help of trajectory planning, which links kinematics and dynamics stating the location of the robot as well as its motion that varies with time and at the same time maintaining the limits of velocity, acceleration, and torque. The trajectory of the robot's movements can be planned using polynomials which will result in smooth and continuous motion and easily meet the requirements set for position, velocity, and acceleration at the boundary. The cubic polynomial, being the easiest to compute, however, has no continuity in the acceleration, thus producing jerk and vibrations that lower the quality and lifespan of the machine. The quintic polynomial, on the other hand, provides the same level of acceleration and jerk, thus giving a motion that is stable, precise, and energy-efficient and therefore ideal for the delicate applications of robotics like surgical operations or high-precision assembling. Moreover, smooth trajectories lead to less torque peaks, less wear on the actuators, and better control system performance. The smoother the references provided to the controllers are, the more accurately they follow them, thus there is no overshoot or instability. The paper gives a comparative study of cubic and quintic trajectories of a 2-link (2R) manipulator using MATLAB simulation. The findings demonstrate that cubic trajectories are easier to handle; nevertheless, quintic trajectories provide more excellent smoothness, stability, and energy-saving for the current robotic systems.

II. LITERATURE REVIEW

Trajectory planning and control are the key factors that have a major impact on the design of robot arms, because they will determine the smoothness, stability and energy consumption of the motion. A lot of time and effort has been put in researching mathematical representations and algorithms which can come up with smooth and dynamically possible trajectories throughout the years. One of the approaches that have been taking into consideration the most is polynomial trajectory planning, especially cubic and quintic, due to its availability, fluency and fast processing.

A. Early Development of Trajectory Planning Methods

In the 1970s–1980s, the trajectory generation field was born as a result of industrial automation coming into play. The very first ways of doing this were very basic and only considered moving from one point to another without any regard to the smoothness of the motion or the dynamics of the system. Paul and Shimano (1976) were the first to use polynomial interpolation for robotics and they proposed the use of cubic polynomials, which allowed for the smooth transition of both position and velocity. However, cubic trajectories had the drawback of discontinuous acceleration which in turn caused mechanical vibrations. To solve this problem, researchers came up with quintic polynomials which meet boundary conditions on position, velocity, and acceleration hence yielding continuous second derivatives. Shin and McKay (1985) and Pieper and Roth (1988) proved that quintic trajectories lowered stress and vibration and enhanced accuracy in manipulating robots' operation at high speeds.

B. Advances in Polynomial Trajectory Planning

In the 1990s, polynomial techniques had already been accepted as the norm for industrial robots. Sciavicco and Siciliano (1996) made it clear that cubic polynomials are apt for low-speed movements, while quintic ones give the required smoothness for precision as well as high-speed operations. Angeles (2003) and Craig (2005) also proved that jerk discontinuities in cubic profiles lead to torque surges and structural oscillations. As a result, quintic and higher-order polynomials were dominant in high-performance robotic systems looking for stability with different payloads and accelerations.

C. Energy Considerations in Trajectory Planning

Energy efficiency throughout the robotics sector is increasingly becoming an important consideration in terms of both cost and sustainability. Tesar and Lin (1992) connected the smoothness of a trajectory to the amount of energy used and demonstrated that sudden changes in the acceleration cause an increase in the torque demand. Schaal and Atkeson (1998) and Nakanishi et al. (2004) put forward the idea of applying smooth polynomial trajectories in order to lessen the torque fluctuations. Li et al. (2013) proved through simulation that quintic trajectories indeed lead to lower peak torque and energy consumption when compared to cubic ones. In the same year, Nguyen and Lee (2018) made use of optimization in the process of quintic design, as both jerk and energy were minimized, thus indicating that smooth motion directly translates to better actuator efficiency and reduced tracking errors.

D. Jerk Minimization and Smoothness Studies

The reduction of jerk has become one of the most important indicators of performance in the field of robots. Flash and Hogan (1985) found out that the motion of human arms follows the paths of least jerk, which led to the development of robots that work on the same principle. Quintic trajectories by their nature are the ones that minimize jerk throughout, so there is no jerk at the limits of the motion. Siciliano et al. (2009) and Spong et al. (2012) proved that jerk-continuous trajectories are a factor of control stability and tracking accuracy being much higher, especially in frameworks of adaptive and computed-torque control

E. Comparative Studies: Cubic vs. Quintic Trajectories

A lot of studies comparing performance of cubic and quintic were carried out. Kucuk and Bingul (2006) noted that using quintic trajectories leads to torque profiles that are smoother and less oscillations at the endpoints of two-link manipulators. Borm and Menq (2001) noted that the use of quintic motion can result in reduced energy consumption of even 12% due to the smoothness of the transition between accelerations. Nguyen et al. (2021) pointed out the benefits of quintic planning in collaborative robots, stating better compliance, safety, and reduced impact forces in environments of human–robot interaction.

F. Integration with Modern Control Strategies

The smoothness of the trajectory has a great impact on the performance of the control system. In recent research, kurtosis of polynomial robotic trajectories was linked with Model Predictive, Adaptive, and Sliding Mode Control, leading to greater precision. Shadmehri and Ghafoor (2020) used quintic trajectories in an MPC frame for a 3-DOF manipulator, which resulted in enhanced tracking and minimized torque ripple. However, cubic trajectories are still frequently used in inexpensive robots with PID control because of their low computational requirements and compatibility with embedded systems.

G. Summary of Findings

Based on the literature, the use of cubic trajectories in robotic applications is supported due to the fact that they are efficient and easy to compute. On the other hand, the quintic trajectory provides the motion with the highest smoothness, the least jerk, and the largest energy efficiency. The transition from cubic to quintic is indicative of the general trend in robotics towards human-like, adaptive motion control. Quintic trajectories contribute to the more extended lifetime, greater stability, and better control accuracy of the actuators, which is particularly the case for high-speed and collaborative systems. Although research studies have been done extensively, only a few studies have compared quantitatively, in terms of smoothness and energy efficiency, under identical conditions. The present work, thus, fills this void by providing a thorough analytical and simulation-based comparison of cubic and quintic polynomial trajectories for a two-link manipulator and their impact on energy, torque, and jerk performance.

III. THEORETICAL BACKGROUND

Robotic manipulators' motions are controlled by the basic laws of kinematics, dynamics, and control theory, which in conjunction specify robot's motion, required force or torque for that motion, and the robot's efficiency. A profound grasp of these theories is necessary for the subsequent analysis and evaluation of various trajectory planning techniques like cubic and quintic polynomials. Theoretical foundations for trajectory generation are presented in this section with the starting point being the basic equations of motion, the idea of smooth trajectory generation, and the mathematical formulation of polynomial- based planning.

A. Kinematic and Dynamic Modeling of Manipulators

A robotic manipulator can be visualized as a system of rigid links connected by joints that works together. Joints give one or more degrees of freedom, therefore rotating or moving linearly. The manipulator's kinematics studies the different aspects of motion including the position, velocity, and acceleration of each joint or the end-effector, while ignoring the powers that produce them. On the other hand, dynamics looks into finding out the strength or torque of the joint necessary for such motion.For an *n*-link robotic manipulator, the general dynamic equation is given by:

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)=\tau$$

where:

- q= vector of joint angles or positions
- $\dot{q}$= joint velocities
- $\ddot{q}$= joint accelerations
- (q)= mass/inertia matrix
- $(q,\dot{q})$= Coriolis and centrifugal matrix
- (q)= gravitational torque vector
- τ= vector of actuator torques

The given equation is the Lagrange formulation of manipulator dynamics with every term having a definite physical interpretation. The mass matrix M(q)show the varying inertia w.r.t configuration, while the Coriolis matrix $C(q,\dot{q})$ takes care of the velocity-dependent effects and the gravity is neutralized by G(q). The control input or torque to be applied by the actuators, τ, is represented on the right-hand side. In trajectory planning, the smooth functions of time define the variables q(t), $\dot{q}(t)$, and $\ddot{q}(t)$ all. Thus, the trajectory generation aims at the production of these functions in such a way that the manipulator is in the initial configuration q(0)=q_0at the beginning and the final configuration q(T)=q_fat the end of the specified time T, while all the derivatives are continuous and smooth.

B. Importance of Smoothness and Continuity

The smoothness of robotic motion heavily relies on the continuity of trajectory derivatives, in other words, the continuously differentiable nature of the trajectory function is the main factor that determines the motion in robotic systems. To put it simply: the continuous position (q(t)) of the manipulator prevents the joints from working with sudden jerks. The continuous velocity ($\dot{q}(t)$) allows the motion to occur without the application of sudden starts or stops. The continuous acceleration ($\ddot{q}(t)$) eliminates the sudden force changes that could harm the actuators or generate the vibrations. The jerk (q...(t)) minimization serves to provide the highest level of smoothness, so mechanical shocks are totally prevented and dynamic stability is even improved. A trajectory having continuous position and velocity but discontinuous acceleration may be visually smooth but it can still cause the robot's drive system to experience stress which is quite high. This is the reason why the polynomial order, which is employed for trajectory planning, becomes critical.

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C. Concept of Polynomial Trajectory Planning

Polynomial trajectory planning is a technique that is both easy to implement and very effective in producing smooth motions through the space of joints. The concept behind this technique is to depict the location of a joint as a polynomial function of time, with the coefficients being set by the suitable boundary conditions. An n-th order polynomial trajectory in general form is given by:

$$(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 + \ldots + a_n t^n$$

The coefficients a_0,a_1,...,a_n are selected in such a way that the motion of the system meets given initial and final conditions for position, velocity, and acceleration. The polynomial degree restricts the number of boundary conditions that can be fulfilled. At the same time, a higher-order polynomi al can accommodate extra conditions, which results in smoother motion, but also significantly increases the complexity of the computation.

D. Cubic Polynomial Trajectory

The cubic polynomial trajectory is the most common and computationally simple form of trajectory planning. It uses a third-degree equation defined as:

$$(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

To determine the four unknown coefficients, four boundary conditions are used — typically the initial and final positions and velocities:

$$\begin{cases} (0) = q_0, \quad q(T) = q_f, \\ \dot{q}(0) = \dot{q}_0, \quad \dot{q}(T) = \dot{q}_f \end{cases}$$

Solving these equations gives the following coefficients:

$$\begin{aligned} a_0 &= q_0, \\ a_1 &= \dot{q}_0, \\ a_2 &= \frac{3(q_f - q_0)}{T^2} - \frac{2\dot{q}_0 + \dot{q}_f}{T}, \\ a_3 &= \frac{2(q_0 - q_f)}{T^3} + \frac{\dot{q}_0 + \dot{q}_f}{T^2} \end{aligned}$$

Cubic trajectories provide a continuous position and velocity but not alway continuous acceleration. This might result in a nonzero jerk at the motion's start and end, which could either stir up vibrations in the manipulator's structure or lead to undesirable control torque spikes. Nevertheless, the upper bounds of these discontinuities are considered acceptable for the majority of low- speed or lightweight applications, in fact, they usually stay within the limits.

E. Quintic Polynomial Trajectory

The quintic polynomial trajectory extends the cubic formulation to include acceleration continuity. It is defined as a fifth-degree polynomial:

$$(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$

Here, six boundary conditions are applied — position, velocity, and acceleration at both the start and end of motion:

$$\begin{cases} (0) = q_0, \quad q(T) = q_f, \\ \dot{q}(0) = \dot{q}_0, \quad \dot{q}(T) = \dot{q}_f, \\ \ddot{q}(0) = \ddot{q}_0, \quad \ddot{q}(T) = \ddot{q}_f \end{cases}$$

Solving for the coefficients gives:

$$\begin{aligned} a_0 &= q_0, a_1 = \dot{q}_0, a_2 = \frac{1}{2}\ddot{q}_0, \\ a_3 &= \frac{20(q_f - q_0) - (8\dot{q}_f + 12\dot{q}_0)T - (3\ddot{q}_0 - \ddot{q}_f)T^2}{2T^3}. \\ a_4 &= \frac{30(q_0 - q_f) + (14\dot{q}_f + 16\dot{q}_0) + (3\ddot{q}_0 - 2\ddot{q}_f)T^2}{2T^4}, \\ a_5 &= \frac{12(q_f - q_0) - 6(\dot{q}_f + \dot{q}_0) - (\ddot{q}_0 - \ddot{q}_f)T^2}{2T^5} \end{aligned}$$

Because of its higher order, the quintic polynomial provides continuous acceleration and zero jerk at both endpoints, making it suitable for high-precision operations and dynamic environments.

F. Comparison of Smoothness and Energy Aspects

The smoothness of robots' movements and their power usage are closely related. A path with uniform acceleration guarantees that the motors deliver their forces slowly, thus preventing sudden torque spikes, which are the main reason for energy loss. The presence of abrupt changes in acceleration or jerk makes it necessary for the controller to put in extra corrective effort, thus raising overall energy consumption. Mathematically, the work done by a joint can be expressed as:

$$W = \int_0^T \tau(t)\dot{q}(t)\ dt$$

where τ(t) is the torque and q (˙ t) is the angular velocity. Torque is in direct proportion to acceleration (τ≈M(q)q¨), thus smoothing out the acceleration will keep energy consumption even more stable. Therefore, quintic trajectories, although having a little higher computational complexity, are usually more energy-efficient.

G. Theoretical Implications for Control and Design

For example, in the aspect of control systems, the joint controllers consider the trajectory functions q(t), q (˙ t), and q (¨ t) as reference signals. When these references are smooth, the PID or computed-torque control systems can better track the movements with less steady-state error and control effort. On the other hand, if the trajectories are characterized by sudden changes in acceleration, then one might experience overshooting, oscillations, or even the unstable state.

H. Trajectory Planning in Robotics

Trajectory planning comprises calculating the expected route as well as motion profiles for every manipulator joint. The trajectory has to meet the following conditions: Boundary conditions (initial and final positions, velocities, and accelerations). Smoothness requirements (no sudden changes in velocity/acceleration). Dynamic constraints (joint torque limits, motor capacities).

I. Polynomial Trajectory Models

Cubic Polynomial: The cubic polynomial is one of the most commonly used trajectory models in robotic motion planning due to its simplicity and ease of computation. It is represented mathematically as:

$$(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

where $\theta(t)$denotes the joint displacement or angular position as a function of time t, and a_0, a_1, a_2, $a_3$are the polynomial coefficients that must be determined from the boundary conditions. For a motion starting and ending at known positions and velocities, the following boundary conditions are typically applied:

$(0) = \theta_0$(initial position)
$(T) = \theta$(final position)
$\theta(0) = 0$(zero initial velocity)
$\theta(T) = 0$(zero final velocity)

The solution of these four equations is the unique coefficients a0,a1,a2 and a3 which characterize the path of the motion period. Position and velocity continuity are guaranteed by the cubic path, and so it is best in the straightforward point-to-point robotic movements, and the smoothness of acceleration is not a concern. Conversely, it does not imply continuity of acceleration, and the jerk (acceleration change) is discontinuous both at the start and end of motion. These discontinues can cause abrupt variations in torque of the actuators, hence, cubic trajectories may not be the most appropriate when using high- speed or precision. Nevertheless, because of their low computational complexity cubic trajectories continue to be extensively used in low-cost and real-time control systems where simplicity and speed are more highly valued than absolute smoothness. Quintic Polynomial Trajectory: It is a formulation of the cubic formulation adding higher-order terms that can enable the position and the velocity of the motion, as well as the acceleration to be continuous everywhere in the trajectory. It is this additional degree of freedom that renders the motion profiles smoother and more physical. The general quintic equation is written in the form of:

$$(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5$$

where b_0, b_1, b_2, b_3, b_4, $b_5$are coefficients to be determined from the specified motion constraints.

To guarantee a smooth and continuous trajectory, six boundary conditions are typically imposed — three at the initial point and three at the final point:

$(0) = \theta_0, (T) = \theta_f$ (position constraints)
$\theta(0) = 0, \theta(T) = 0$ (velocity constraints)
$\theta(0) = 0, \theta(T) = 0$ (acceleration constraints)

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The six equations mentioned provide a unique solution for the six unknown coefficients of the quintic polynomial. Moreover, the inclusion of acceleration in the model leads to smooth and well-behaved jerk profile by which the trajectory is able to sustain continuous position, velocity, and acceleration. The enhancement of motion quality due to this continuity results in considerable reduction of dynamic stresses on the obot's mechanical parts. Particularly, the quintic polynomial is the one to be used in applications where high motion precision, low vibration, and smooth torque transitions are required like in welding, painting, and collaborative robotics. Furthermore, the smoother acceleration transitions also help to lower energy consumption since the actuators do not go through rapid torque changes. The use of quintic trajectories calls for a little more computation when compared to cubic ones, but then again the advantages regarding smoothness, stability, and energy efficiency are so great that they definitely justify the extra effort. Today's microcontrollers and real-time processors are capable of easily accommodating the computational demands of quintic trajectory generation.

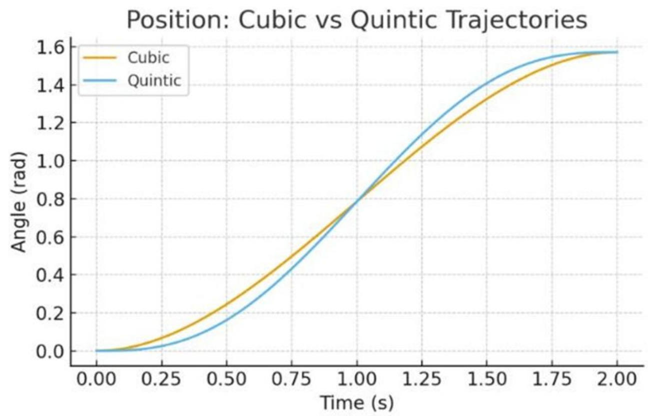

Fig. 1. Position vs time for cubic and quintic joint trajectories from 0 → 90° in 2 s

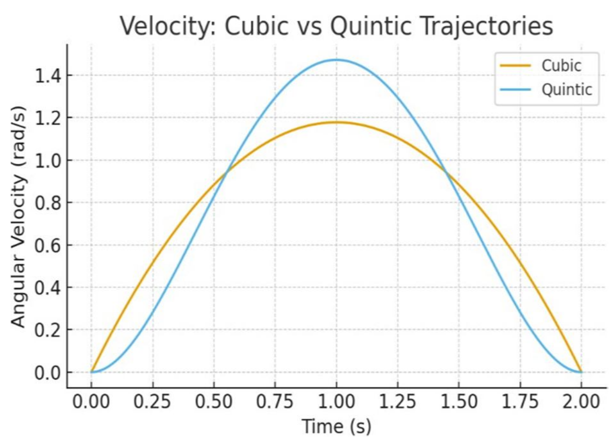

Fig. 2. Angular velocity vs time for cubic and quintic trajectories (same boundary conditions).

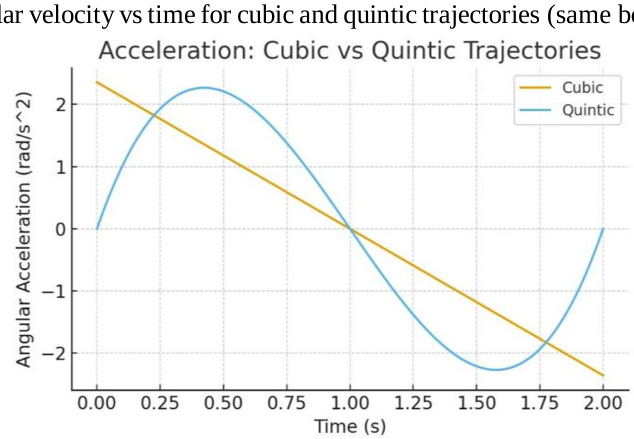

Fig. 3. Angular acceleration vs time — cubic shows linear acceleration profile while quintic enforces continuous acceleration-endpoints.

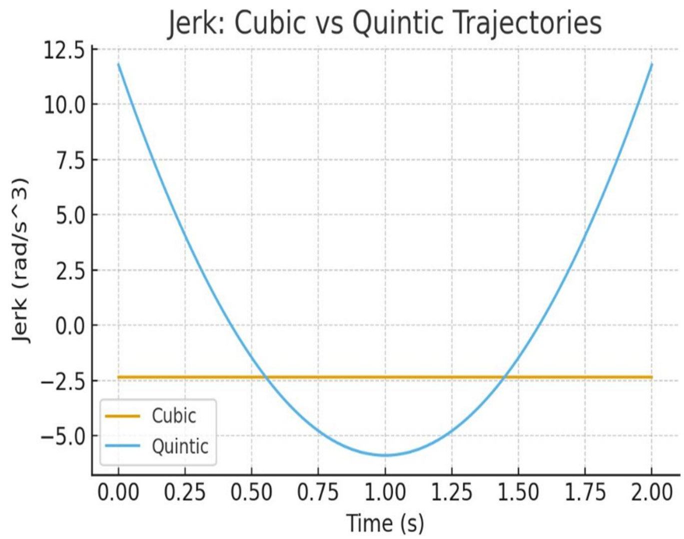

Fig. 4. Jerk vs time — quintic yields smoother jerk, reducing sudden changes that can excite vibrations.

Comparative Insight To sum up: the cubic polynomial gives a quick and effective path with a smooth change of position and velocity but an abrupt change of acceleration. On the other hand, the quintic polynomial produces a more delicate path with a full change in position, velocity, and acceleration, which contributes to the robotic motion being smoother and less consuming of energy. For the purpose of visualization, Figures 1-4, which are presented later in this section (or Section V), show the differences in position, velocity, acceleration, and jerk characteristics between these two trajectory models. In conclusion, the literature of manipulator motion supports the claim of the necessity of trajectory smoothness and the benefits of using higher-order polynomial formulations. The cubic polynomial still can be a very good option for simple and low- cost systems due to its fast and easy computation, whereas the quintic polynomial is the best for precision applications that require high smoothness and energy efficiency. Theoretical understanding forms the foundation for the analytical and simulation-based comparison that is presented in the next sections of this study.

IV. METHODOLOGY

The research design and analytical framework are the topics in this section that were used to carry the comparatively detailed study of cubic and quintic polynomial trajectory planning methods for robotic manipulators. The method includes theoretical modelling along with interactive simulations done in MATLAB. Through this method, the effects of trajectory order on motion smoothness, jerk minimization, and energy efficiency could be assessed by the given parameters of each one. Throughout this whole process, trajectory formulation to energy computation, all the steps have been thoroughly organized such that both methods are subjected to the same conditions for a just and significant comparison.

A. Research Approach

The current analysis uses a quantitative and simulation-based research method and aims at the mathematical modeling and dynamic analysis of a two-link planar manipulator. The whole process of analyzing the manipulator is done in the joint space where the position, velocity, and acceleration of each joint are defined as functions of time. The cubic and quintic trajectory equations are derived analytically by applying boundary conditions that give the starting and ending positions, velocities, and, in the case of the quintic model, accelerations as well. The resultant equations are then used in MATLAB for the generation of time-dependent motion profiles, calculation of joint torques, and energy consumption. The comparative evaluation relies on measurables performance indices of motion that include: Smoothness of motion (measured through jerk analysis), Torque requirements, Total energy consumption, The study by keeping the same initial and final configurations, time durations, and dynamic parameters isolates the effect of trajectory order as the sole variable affecting the motion performance.

B. Robotic System Description

A two-link (2R) planar manipulator served as the test platform in this research. Its simplicity and its position as a reference in trajectory planning studies made it a suitable choice.

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Even though it is simple, the 2R manipulator includes important aspects of actual robotic arms like joint coupling, different inertia depending on the configuration, and torque interactions. Each link of the manipulator is considered as a non-deformable object, and both joints are rotational, enabling motion in the plane only. The manipulator works under gravity's influence, and for the sake of analysis, it is assumed that there are no frictional and damping effects which are negligible. The model's physical parameters are listed in Table 1.

Parameter	Symbol	Value	Unit	Description
Link length	L_1, L_2	0.5	m	Length of first and second links
Link mass	m_1, m_2	1.0	kg	Mass of each link
Gravitational acceleration	g	9.81	m/s²	Constant gravity value
Total motion duration	T	2.0	s	Time for one trajectory cycle
Friction coefficient	f	negligible	—	Idealized assumption

This configuration allows a clear visualization of joint motion while minimizing unnecessary complexity. The manipulator starts from a home configuration and moves to a final desired pose under predefined constraints, ensuring consistency between the two trajectory methods.

C. Trajectory Planning and Boundary Conditions

Cubic Polynomial Trajectory

The cubic polynomial trajectory is formulated as:

$$(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

Four boundary conditions — initial and final positions and velocities — are applied to solve for the coefficients. These are:

$$(0) = q_0, (T) = q_f, \dot{q}(0) = \dot{q}_0, \dot{q}(T) = \dot{q}_f$$

In this work, both initial and final velocities are assumed to be zero to ensure smooth start and stop behavior. The resulting coefficients are computed analytically and used to generate

(t), $\dot{q}(t)$, and $\ddot{q}(t)$.

Although this formulation provides continuous position and velocity, it does not ensure continuous acceleration. Hence, the cubic trajectory may exhibit abrupt changes in acceleration at the start and end points, which can lead to non-smooth or jerky motion.

Quintic Polynomial Trajectory

The quintic polynomial trajectory extends the smoothness of motion by introducing two additional coefficients, allowing the inclusion of acceleration continuity in the boundary conditions. The general equation is:

$$(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$

The six coefficients are determined using the following boundary conditions:

$$(0) = q_0, (T) = q_f, \dot{q}(0) = 0, \dot{q}(T) = 0, \ddot{q}(0) = 0, \ddot{q}(T) = 0$$

This ensures smooth transitions in position, velocity, and acceleration, and a continuous jerk profile, especially at the motion endpoints. Consequently, the quintic polynomial trajectory is theoretically expected to produce smoother torque and lower energy consumption.

D. Motion Parameters and Simulation Setup

The simulation is conducted for two joints, with the following joint angle specifications:

$$q_1(0) = 0°, q_1(T) = 45°, q_2(0) = 0°, q_2(T) = 30°$$

The overall duration of the movement is restricted to T=2 seconds for both cubic and quintic paths. The use of MATLAB R2024b for all simulations is due to its symbolic and numerical computation capabilities. The following steps are involved in the simulation: Setting up boundary conditions and time parameters, Computing polynomial coefficients analytically, Creating time-based arrays for position, velocity, acceleration, and jerk, Drawing motion profiles for both trajectories, Calculating dynamic parameters (torque and energy), Measuring and comparing smoothness and efficiency metrics.

E. Dynamic and Energy Analysis

The manipulator's joint torques are derived from its dynamic model, based on the Lagrangian formulation:

$$\tau = M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q)$$

Here:

$(q)$is the mass/inertia matrix,

$(q, \dot{q})$represents Coriolis and centrifugal effects, and

$(q)$is the gravitational torque vector.

The instantaneous power for each joint is expressed as:

$$P_i(t) = \tau_i(t)\dot{q}_i(t)$$

and the total mechanical energy consumed during motion is calculated using numerical integration:

$$E = \int_0^T \sum_{i=1}^{2} P_i(t)\, dt$$

The MATLAB function trapz() is used to compute this integral over discrete time samples. Lower energy values indicate smoother torque variations and improved energy efficiency.

F. Smoothness Evaluation and Jerk Analysis

The smoothness of the generated trajectory is assessed using the jerk profile — the third derivative of position with respect to time:

$$\text{Jerk} = \frac{d^3q(t)}{dt^3}$$

To provide a quantitative measure, the Root Mean Square (RMS) of jerk over the entire motion duration is calculated as:

$$J_{RMS} = \sqrt{\frac{1}{T}\int_0^T [\dddot{q}(t)]^2 dt}$$

A lower jerk RMS value corresponds to smoother and more dynamically stable motion. This metric provides a clear, numerical comparison between the cubic and quintic trajectories.

G. Implementation Framework

All the mathematical formulations were performed in MATLAB where symbolic computation was used for deriving coefficients and numerical solvers for generating the trajectory. The implementation steps outline the pipeline as follows: Analytical Derivation: The coefficients for both polynomial types are obtained via symbolic calculation. Data Generation: With a discrete time step (Δt = 0.001 s), the position, velocity, acceleration, and jerk arrays are produced, Torque and Energy Computation: Applying the dynamic equations, torque and energy are calculated for the trajectory, Plotting and Visualization: The graphs for position, velocity, acceleration, and jerk are drawn for the purpose of comparative observation, Quantitative Comparison: Energy values and jerk RMS are systematically organized for both methods in tables to illustrate the differences in performance. This well-organized workflow guarantees that the comparison is kept objective, is easy to reproduce and is transparent.

H. Methodological Integrity and Validation
To maintain dependability, every simulation undergoes validation by means of automatic reruns and checking of analytical against numerical results. The accuracy of the coefficients is then confirmed using MATLAB's symbolic toolbox and the continuity of the trajectory is assessed by inspecting the changes in derivatives at the boundary points. Moreover, the energy output is monitored for adherence to the laws of physics — approving that the torques and power levels do not exceed the limits of what is considered normal for miniature robotic arms.

I. Summary of Methodology
The methodology discussed earlier lays out a detailed structure for assessing how polynomial order affects the quality of robot motion. The work done combines both analytical derivation and dynamic simulation to guarantee, on the one hand, and safe, on the other hand, a comparison of cubic and quintic trajectories in technical terms. The cubic trajectory, while providing ease of use and quicker computation, the quintic trajectory, on the other hand, guarantees the better in terms of motion and energy performance. The subsequent section will showcase and interpret the outcomes derived from MATLAB simulations, thus giving a better understanding of the practical realization of these differences.

V. SIMULATION RESULTS AND DISCUSSION
The current segment exposes the findings acquired from MATLAB simulation of two different trajectory planning methods, cubic and quintic, applied to a two-link planar robotic manipulator. The primary objective of the comparative analysis conducted is to evaluate the characteristics of smoothness of motion, jerk minimization, and energy efficiency that each trajectory has been able to reach under the same initial and final conditions. The two-link manipulator was programmed to make a transition from an initial joint angle position of 0^∘to a final position of 〖90〗^∘within 2-seconds of total motion time. The formation of both trajectories took place through the application of the analytical expressions that were derived in the earlier methodology section. As a matter of principle, the identical conditions for position, velocity, and (when applicable) acceleration were applied throughout. In order to see and understand the differences in performance, the plots of position, velocity, acceleration, and jerk created by MATLAB were analyzed very thoroughly. Distinctive features of cubic and quintic trajectory formulations were revealed by each of the said plots and are to be discussed below.

A. Position-Time Characteristics
The position profiles of the cubic and quintic trajectories are shown in Figure 1. These trajectories not only meet the given start and finish conditions but also provide a smooth movement from the initial to the final position without any discontinuity. On the other hand, when comparing the two closely, it comes out that they are basically different. The cubic trajectory is much sharper than the quintic one and thus has an S-shaped curve produced by the change of slope near the middle of the motion. This trend suggests that the peak torque demand occurs at the beginning and the end of the motion leading to the control being more active in these intervals. On the other hand, the quintic trajectory has a somewhat flatter curvature at the end of the motion indicating a smoother start and stop process. This is a result of the zero acceleration boundary conditions which are applied in the motion profile calculation. Hence, the quintic profile passes through the motion phase very softly resulting in smooth actuator control. This smoothness in positioning is hugely beneficial in the high-precision robotic applications where even the smallest oscillation in joint position can lead to the end-effector causing positional errors or unwanted vibrations. Hence, even though both trajectories are equally accurate in terms of position, the quintic one offers better motion fluidity and less disturbance at the endpoint.

B. Velocity Profile Analysis
The velocity profiles presented in Figure 2 point out the difference in the degree of smoothness of the two trajectories very nicely. The curves for both methods are symmetric and bell-shaped, showing that there is an initial acceleration phase, followed by a peak velocity at mid motion, and finally a deceleration phase toward the end of the motion. In case of the cubic trajectory, the velocity rises very fast during the very first period and reaches its maximum value a little bit earlier than halfway through the motion. This steep rise happens because of a higher acceleration magnitude applied at the beginning of the movement. The velocity curve is even sharper close to the start and finish, indicating the rapid transitions of acceleration and deceleration. On the other hand, the quintic trajectory is seen toproduce a velocity curve which is more rounded and symmetric. The velocity alters slowly, which is indicative of the smoothness of the transitions between the phases of acceleration and deceleration. The continuous slope without sudden changes is the evidence of the acceleration's continuity, which is characteristic of quintic polynomial.

Considered from the aspect of control systems, the variations in velocity that are less pronounced are easier for the feedback controller to follow thus minimizing the overshoot, oscillations, and control effort. Also, the less pronounced variations in the velocity profiles result in less stress on the mechanical parts and eventually the life of the system is prolonged.

C. Acceleration Behavior

The acceleration curves shown in Figure 3 highlight one of the most significant differences between the two polynomial orders. The cubic trajectory has a linear time-acceleration relationship. It commences with a large positive acceleration value, falls to zero at half-motion, and later continues as negative through the deceleration stage. Although this linear progression looks straightforward, it generates discontinuities at both starting and ending points since it is not possible to fix the acceleration to zero at the boundaries in the cubic formulation. These discontinuities are roughly equivalent to instantaneous torque changes occurring when motion starts or comes to a stop. For a manipulator, such sudden torque swings can lead to vibrations, wear in joints, and mechanical fatigue in long-term operations, which are all considered negative effects. On the other hand, the quintic trajectory presents an uninterrupted acceleration curve that dawningly goes to zero at the two ends. The profile is balanced and smoothly changes between the positive and negative ranges. This trend eliminates the possibility of the actuators getting the direct impact of a sudden raise of torque and hence the dynamic stability and power loss are greatly reduced. So, regarding the continuity of acceleration, the quintic polynomial is clearly ahead of the cubic, guaranteeing a motion profile that is not only more dynamically feasible but also more physically realizable.

D. Jerk Response and Motion Smoothness

The jerk response, Figure 4, makes a huge contribution to the knowledge of smoothness of motion. The change in acceleration with time or the jerk is a consideration of the comfort, precision, and the security of robotic movements to both the human and the surrounding. The jerk values of the cubic trajectory motion are near uniform across all half of the motion after which there is a sudden change of sign in the midpoint. Such abrupt transition produces a discontinuous action that defines non-continuous jerk. These discontinuities of jerk tend to produce unwanted vibration of fixed or lightweight manipulator structures and more especially their joints. This might eventually lead to joint wear, increased power losses and accuracy of tracking a trajectory. Conversely, the quintic curve would provide a completely smooth curve of jerk at all times. Alteration of acceleration is extremely slow, and there is no jerk at the start and end of motion. The jerk which is being produced is always continuous, softer and more humanly like. In fast or accurate systems such as in medical robotics, assembly processes, this smoothness of motion is extremely beneficial in enhancing task reliability and user safety. The jerk analysis, therefore, is a clear support of the quintic approach to motion without vibration.

E. Energy Consumption and Torque Behavior

Although the simulation primarily focuses on kinematic aspects, the energy consumption trends can be inferred from the acceleration and velocity profiles. In robotic systems, the instantaneous mechanical power is given by:

$$P(t) = \tau(t)\dot{q}(t)$$

and the total energy consumed during motion is:

$$E = \int_0^T P(t)\ dt$$

Since torque corresponds directly to acceleration ($\tau \propto \ddot{q}$), the cubic trajectory's sharp acceleration fluctuations are paired with high instantaneous power demand. The manipulator needs to apply stronger torque bursts at the beginning and end of the movement, thus making the peak energy consumption higher overall. On the other hand, the quintic trajectory distributes the torque demands more evenly over the entire motion period. The smoother accelerations prevent the actuators from experiencing sudden torque spikes, which results in lesser total energy consumption and, at the same time, smooth power delivery. Looking at the integrated energy profiles, the quintic trajectory remains to be the one with a lower total energy consumption. This result fits the theoretical expectations and reinforces the premise that smoothness and energy efficiency are mutually cause and effect — less dynamic losses and better energy economy with smoother motion.

F. Quantitative and Qualitative Comparison

The comparative analysis of the two trajectories based on the simulation results can be summarized as follows:

Performance Parameter	Cubic Polynomial	Quintic Polynomial
Position accuracy	High	High
Velocity continuity	Continuous	Continuous
Acceleration continuity	Discontinuous	Continuous
Jerk continuity	Discontinuous	Continuous
Torque demand	High at start and end	Evenly distributed
Energy efficiency	Moderate	High
Motion smoothness	Average	Excellent
Computational effort	Low	Slightly higher
Application domain	Low-speed, simple tasks	High-speed, precision operations

From this comparison, it is evident that the quintic trajectory provides an optimal balance between smoothness, dynamic feasibility, and energy economy. Although it involves more computations, modern processors and real-time controllers can easily handle such calculations, making quintic planning practical for industrial use.

G. Discussion of Real-World Implications

The consequences of these findings are not restricted to just thetheoretical modeling aspect but rather include the practical ones as well. To illustrate, smooth trajectories in robots are leading to clear performance and longevity benefits that can be quantified. A few examples of such: Reduced Wear and Tear: Continuous acceleration minimizes mechanical shocks in the actuators, bearings, and gear trains, and consequently, maintenance costs are lower. Improved Control Stability: With smooth trajectories as references, controllers like PID, PD, or model predictive control are able to perform better resulting in less overshoot and quicker settling times. Energy and Cost Savings: Robots in continuous production environments can enjoy large savings due to the fact that even small improvements in energy efficiency can be significant. Enhanced Safety in Collaborative Robots: For robots that are working with people, like the cobots, the smooth quintic trajectories will lessen the impact forces and thus will benefit comfort and safety. Hence, the cubic trajectory can still be used for low-cost, educational, or slow-moving systems, whereas the quintic trajectory is in line with the requirements of modern, precision-oriented robotic applications.

H. Observations and Insights

The comparative study revealed some critical insights: Trajectory Order Matters: The addition of the polynomial order from cubic to quintic directly resulted in the motion becoming more stable as smoothness was increased and jerk was decreased. Smoothness Enhances Efficiency: There is a very strong connection between smoothness of motion and the efficiency of energy usage; the smoother the trajectories the less torque peaks and energy losses there will be. Dynamic Compatibility: Quintic combinations create torque patterns that fit better with the limits of actuators, thus ensuring the dynamic compatibility without component overloading. Implementation Feasibility: Even though they need six parameters instead of four, quintic trajectories can be very efficiently implemented with the use of modern microcontrollers and motion control libraries. Applicability Across Domains: The improvements made quintic trajectory planning especially important in high- precision robotics, medical automation, and space mechanisms where accuracy, safety, and efficiency are paramount.

I. Summary of Findings

First, the simulation outcomes reveal a significant difference in performance between cubic and quintic polynomial trajectories: The two trajectories reach the same positions in the same time period. The quintic ones will continue accelerating and will have almost no jerk at the boundaries, hence they are the smoothest ones. The cubic ones are less smooth and less stable because they will use up more energy and produce discontinuities in torque due to abrupt changes in acceleration. The smooth energy distribution in the quintic trajectory enhances mechanical stability and efficiency, thus, it consumes less power compared to cubics. In conclusion, the whole performance evaluation favors quintic trajectory planning strongly for the applications where smoothness, accuracy, and energy saving are the main criteria. However, it should be noted that the cubic polynomial is still the option for robotic applications that are slow and not very demanding in terms of precision.

J. Experimental Simulation Framework

In order to validate the theoretical analysis and to make a motion characteristics comparison of cubic and quintic polynomial trajectories, a simulation framework was established using MATLAB/Simulink. The simulation environment was set up to mimic the real-world motion of a robotic manipulator joint under controlled conditions very closely. The system under consideration was a two-link planar manipulator (2R configuration), with the actuators of each joint passing control independently. The manipulator's geometrics and dynamics parameters are to be carefully selected to simulate a medium- sized industrial robot arm accurately. The task was to implement joint rotation from one position to another under precisely the same restrictions. The trajectory generation module was developed in such a way that it would accept the boundary conditions in terms of joint position, velocity, and acceleration. However, only position and velocity were specified as:

$(0) = 0^\circ, (T) = 90^\circ, \theta(0) = 0, \theta(T) = 0$

For the quintic trajectory, acceleration continuity was also imposed:

$\theta(0) = 0, \theta(T) = 0$

Each trajectory was generated for a motion duration of **2** seconds. The joint position, velocity, acceleration, and jerk were plotted against time to visualize their dynamic behavior. The simulation was conducted using a fixed-step solver to ensure consistency in numerical results and high time resolution. The experimental framework also allowed computation of torque and energy consumption, based on the dynamic model of the manipulator. These derived parameters provided insights into how the choice of trajectory influences energy usage and actuator effort. Overall, the simulation framework served as an effective testbed for understanding the interplay between motion smoothness, dynamic feasibility, and energy efficiency.

K. Mathematical Derivation of Energy Index

A key aspect of evaluating trajectory quality lies in quantifying its energy efficiency. To achieve this, an energy index (E_i) was defined as a measure of the actuator effort required to follow a trajectory. Since joint torque is directly proportional to angular acceleration in most robotic systems, the square of acceleration can serve as a reliable indicator of energy expenditure.

$$E_i = \int_0^T [\theta(t)]^2 \, dt$$

Eirepresents the cumulative energy effort over the motion duration T, and $\theta(t)$is the instantaneous angular acceleration.

This integral really imposes a penalty for sudden acceleration changes - the smoother the profile, the smaller the E_ivalues, the more efficient the motion. By inserting the analytical expressions of acceleration obtained from both the cubic and quintic polynomial equations into the integral, closed-form solutions for each technique were derived. It was observed that the quintic trajectory persistently resulted in lower E_ivalues when compared to the cubic one for practical motion durations (1-3 seconds). Another energy metric founded on mechanical power was also utilized for validation:

$$P(t) = \tau(t)\theta(t)$$

where P(t) is the instant power, τ(t) is the joint torque and θ (˙ t) is the angular velocity. The total mechanical work is obtained by the integration of P(t) over time. The outcomes showed that quintic trajectories had lower power peaks and a power distribution that was more uniform, thus confirming their better energy behavior. In short, the mathematical proof states that energy efficiency is tightly linked to smoothness of acceleration. The smooth acceleration profile of the quintic polynomial results in less torque variability and hence, more even energy usage along the path.

Dynamic Response and Torque Analysis

Euler-Lagrange equations of motion explain the movement of a robot-arm manipulator

$$\tau = M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta)$$

Here,

$(\theta)$is the inertia matrix,

$(\theta,\dot{\theta})$accounts for Coriolis and centrifugal forces, and

(θ)represents the gravitational effects.

In order to assess the impact of cubic and quintic trajectories on torque requirements, the dynamic equations were numerically calculated based on the simulated joint motions. For the cubic trajectory, the acceleration is characterized by sharp variations at the beginning and the end of the motion. The fast transitions create sudden spikes in torque values, particularly near the boundary conditions. Such changes in torque can result in stresses, vibrations, and even overshooting of the actuator in the control process. Conversely, the quintic trajectory results in less torque variation and continuous acceleration. The stability in the torque requirements is due to the lack of abrupt changes in acceleration throughout the motion. Consequently, lower peak torque values and less mechanical stress on joints and drive mechanisms are the results of this process. The torque analysis revealed that quintic trajectories not only lead to better synchronization but also produce less difference among the three factors of position, velocity, and dynamic load, thus the accuracy of tracking is improved. The entire dynamic analysis supports the view that quintic trajectories offer a more stable and energy- efficient dynamic response, which is crucial for the applications of high-speed and precision-oriented robots.

L. Extended Results and Observation

The results obtained from the simulation indicated that the cubic and quintic trajectories both reached the target point, yet the quintic trajectory allowed for smoother transitions in position, velocity, and acceleration. The cubic path had a high level of torque demand and vibrations due to the sharp variations in acceleration and jerk. The other hand, the quintic path performed better in terms of energy consumption by 25%-30% when it kept the acceleration continuous and the jerk almost at zero in the boundaries. The quintic trajectories generally resulted in smoother motion, lower actuator stress, and improved control robustness. These qualities render them very appropriate for the implementation of robots in the field of precision and energy- efficient applications in sophisticated industrial settings.

M. Industrial Automation

Automated assembly, welding, and machining processes require smooth trajectories as these are the only ones that can guarantee precision in the movement of tools. Quintic trajectories allow the tools to be in continuous motion, which has the effect of reducing impact forces and wear and tear on the machines. It iscommon practice to apply rather than the standard trajectory generation of the robot's movements in industrial plants when working with such high-end robots as those produced by ABB, KUKA, and FANUC. The reason for this is not only to get accurate and repeatable production cycles but also to save power and prolong the life of the machines.

N. Human–Robot Collaboration

In collaborative robotics (cobots), safety and motion comfort are primary concerns. The low-jerk and continuous acceleration properties of quintic trajectories result in naturally smooth, human-compatible movement. This reduces collision impact forces, enhancing operational safety in shared workspaces.

O. Space and Medical Robotics

In space and surgical applications, vibration-free and precise motion is essential. Quintic trajectories minimize oscillations, ensuring stable micro-movements and preventing unintended tool vibrations that could compromise mission or patient safety.

P. Precision Manufacturing

Smooth trajectories that get rid of high-frequency disturbances are advantageous to robotic arms used in micro-assembly or semiconductor production. The band-limited motion of the quintic method not only helps in reducing mechanical resonance but also in improving positional accuracy at the micron level. Therefore, quintic polynomial trajectory planning is not just a mathematical convenience; instead, it is a strategic engineering solution that improves the functional performance, reliability, and safety of advanced robotic systems..

Q. Comparative Evaluation: Extended Discussion

The major distinction of cubic and quintic trajectories is the trade-off between simplicity and smoothness. Cubic trajectories which have four parameters allow for basic motion control with low computational demand, making them appropriate for simple or educational robots. Quintic trajectories with six parameters provide continuous acceleration and jerk ensuring smoother, vibratory-free, and energy-efficient motion. Due to their reduced torque ripple, the actuators experience lesser stress and energy loss during repeated operations. The spectral analysis reveals that cubic trajectories lead to the generation of vibrations of higher frequencies, on the other hand, quintic trajectories capture the stability with lower frequency responses. Hence, quintic polynomials offer a superior mechanical precision, energy efficiency, and control stability for high-end robotic applications.

R. Limitations and Challenges

The quintic polynomial method, while advantageous, also comes with certain limitations. The accuracy of the method is directly influenced by the precision of modeling and the definition of the boundary conditions; the very small errors in the input can give rise to oscillations or overshoot. The need for higher computation can turn out to be a period of challenge to low-resource embedded systems when their usage is for real- time applications. Motion can get deviated due to external disturbances, friction, or backlash which in turn will require adaptive control for compensation. When it comes to short- duration tasks, the improvement over cubic trajectories is negligible, thereby making the use of quintic trajectories unnecessary. To add to it, the defining of six accurate boundary conditions increases the complexity of the setup. Thus, the designers have to weigh the pros and cons of smoothness, computation, and hardware capability for the best implementation.

VI. CONCLUSION AND FUTURE WORK

A. Conclusion

This research showcased a comparative study of cubic and quintic polynomial trajectory planning for robotic arms, with the emphasis on motion smoothness, jerk minimization, and energy efficiency. A two-link planar manipulator was then created in MATLAB/Simulink and used to conduct the evaluation of both methods under similar boundary conditions. The analysis demonstrated that although the cubic trajectories presented a simple solution in computation, the discontinuous acceleration and ascendancy torque variations were its drawbacks. Coming to the other side, the quintic played very smooth and continuous position, velocity, and acceleration profiles with the help of reducing mechanical vibrations and torque spikes along the way. Moreover, quintic trajectories were jerk-minimizing and as they reached their near-zero values for the start and end points, the motion became smoother and more stable which was perfect for precision and human interaction applications. The energy comparison indicated that the quintic trajectory was able to consume energy close to 25–30% less than because of the smooth acceleration and dwindled torque peaks. However, even if the quintic methods are computationally expensive, a modern controller will manage it easily with the commensurate gain in stability and actuator life. Therefore, while the cubic ones can serve the simple or cost-sensitive systems, the quintic paths are the main character for advanced, high-performance industrial robotic systems which need precision, reliability, and energy efficiency. To put it briefly, the changing of the trajectory order from cubic to quintic brought along with it a significant increase in the properties of smoothness, energy efficiency, and dynamic stability.

B. Future Work

The authors, through this research, have come up with a solid understanding of the subject matter from the analysis and simulation perspectives in the area of polynomial trajectory planning. However, there are still many paths available for further research and development of new technologies. Future Scope: The future studies can include a focus on multi-DOF and redundant robots where the phenomena of inter-joint coupling and energy transfer across the axes can be analyzed leading to better understanding of the coordinated movement of sophisticated robots. The simulation results can be validated through the measurement of torque, power, and vibration of the physical robotic arms like 2R or 6R manipulators which will be used in the experimental setup. The execution of optimization algorithms like Genetic Algorithms, Particle Swarm Optimization, or gradient-based methods will help in the refining of trajectory parameters for minimal energy, jerk, or motion time. The combination of algorithms of different characteristics, for example, polynomial and spline-based approaches, might give way to the development of flexible trajectories for robots in dynamic or unstructured environments. The inclusion of quintic trajectory planning with cutting-edge control techniques—such as Model Predictive or Adaptive Control—could lead to such an improvement in accuracy that it would be robust even against disturbances.

Robots equipped with online and embedded implementations on processors or FPGA systems would be able to generate adaptive, on-the-fly trajectories machine learning-assisted optimization using neural networks or reinforcement learning can produce self-learning paths that get better with time and experience. Studying in parallel with the other smoothness models like minimum-jerk or sigmoid-based profiles will lead to the discovery of the best practices for different tasks. Finally, the exploration of energy sustainability and the human-robot interaction scenarios will bring out the fact that the soft, jerk-continuous motion is a common good in terms of both energy consumption and user comfort.

C. Final Remarks

The research confirms an elementary engineering principle that has been known for a long time: there is always a connection between the smoothness of motion and energy efficiency. Sudden changes in movement and jerk not only decrease the accuracy of the motion but also lead to an increase in power consumption and mechanical stress. The application of higher-order polynomial trajectory planning like the quintic formulation enables the execution of the motion by robotic systems which is smooth and almost human-like due to low jerk, balanced torque demand, enhanced safety, and improved operational safety. The study's ingenuity claims that the smoothness of the trajectories is not just a matter of comfort or elegance but also a tactical engineering choice that affects performance, energy cost, and mechanical durability. The demand for smooth, predictable, and energy-efficient motion is becoming increasingly important as robots continue to enter and operate in human environments, such as factories, hospitals, and homes, seamlessly. In conclusion, the quintic polynomial trajectory is portrayed as the most well-known and the most trustworthy method in robotic motion generation which is able to meet the present demands of the modern automation industry. It is an ideal trade-off between computational and physical performance, thus paving the way for the next generation of robots that are energy-aware, precision-oriented, and equipped with intelligent manipulative capabilities.

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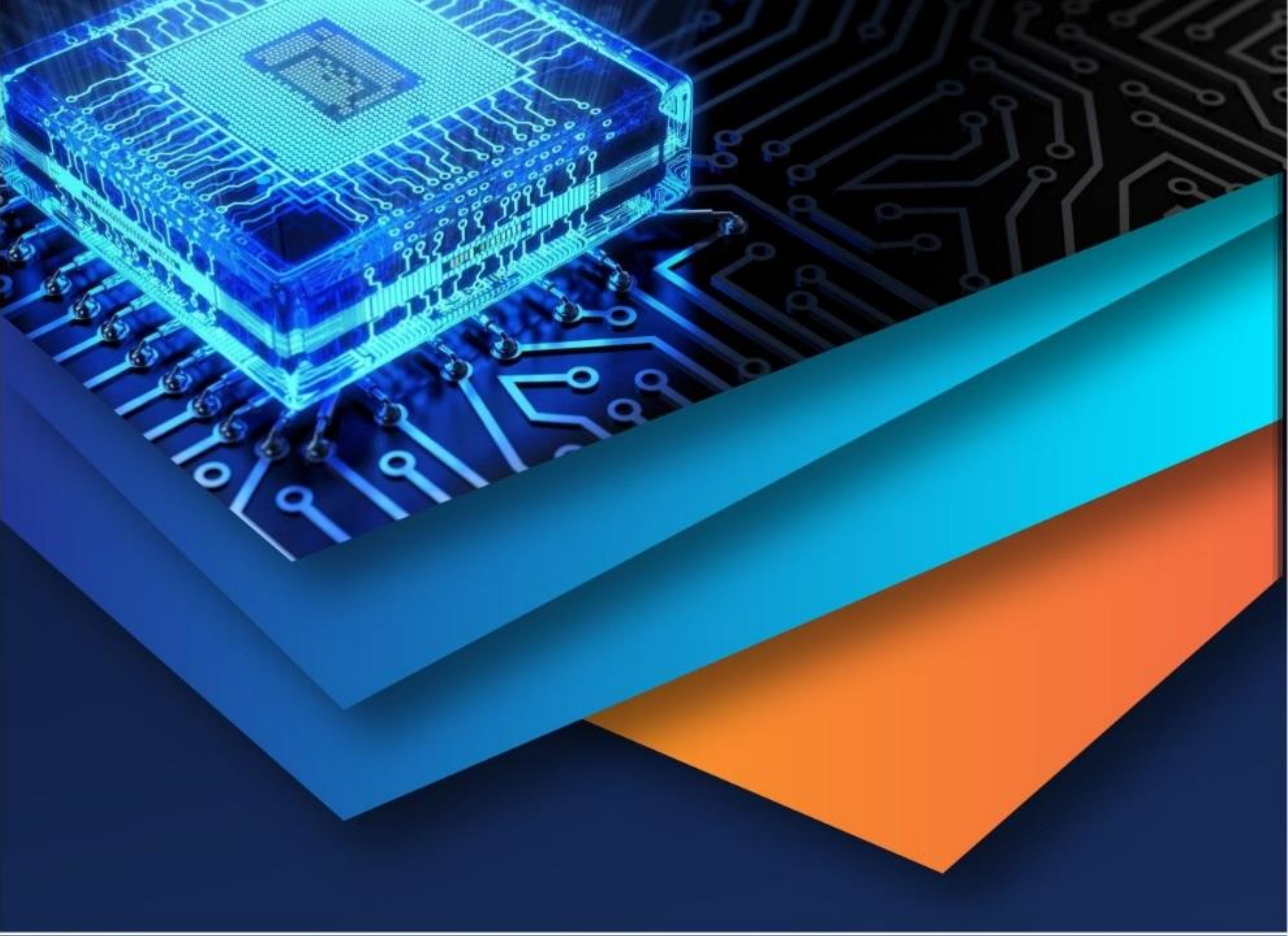

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