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Original Research Article

Model-Based Predictive Command of a 5-DoF Robotic Manipulator using Dynamics Mathematics

Pengendalian Prediktif Berbasis Model untuk Manipulator Robot 5-DoF Menggunakan Model Dinamika Matematis

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Abstract _ *This study presents the design and implementation of a predictive model control (MPC) framework tailored for articulated robot arms, enabling precise local motion control during complex manipulations and interdepartmental transport tasks. The research begins with a systematic formulation of the robot arm's kinematics and dynamics, establishing mathematical models that serve as the foundation for advanced control strategies. A five-degree-of-freedom robotic arm, composed of motor and arm components, is employed as a case study to demonstrate the modeling process and validate the MPC design. Unlike conventional control approaches, the proposed framework emphasizes adaptability and robustness, offering improved trajectory tracking and disturbance rejection. Simulation results highlight the effectiveness of MPC in achieving smoother motion and reduced error margins, with quantitative indicators such as tracking accuracy and computational efficiency underscoring its performance advantages. While the outcomes confirm the feasibility of the approach, limitations related to hardware scalability and real-time implementation are acknowledged. Future work will focus on extending the framework to collaborative robotic systems, integrating sensor fusion for enhanced perception, and exploring deployment in industrial environments. Overall, this research contributes a structured methodology for predictive control in robotics, bridging theoretical modeling with practical application..*

Keywords: *mobile robotic systems, model-based control design, motion control, predictive control, kinematics, and dynamics of articulated robots.*

Abstrak_ Penelitian ini menyajikan perancangan dan implementasi kerangka **Model Predictive Control (MPC)** yang dirancang khusus untuk lengan robot berartikulasi, sehingga memungkinkan pengendalian gerak lokal yang presisi selama proses manipulasi yang kompleks dan tugas transportasi antar departemen. Penelitian diawali dengan formulasi sistematis terhadap model kinematika dan dinamika lengan robot, yang menghasilkan model matematis sebagai dasar bagi strategi pengendalian tingkat lanjut. Sebagai studi kasus, digunakan lengan robot dengan **lima derajat kebebasan (5-DoF)** yang terdiri dari komponen motor dan lengan robot untuk mendemonstrasikan proses pemodelan serta memvalidasi desain MPC yang diusulkan. Berbeda dengan pendekatan pengendalian konvensional, kerangka yang diusulkan menekankan aspek **adaptabilitas** dan **ketahanan (robustness)**, sehingga mampu memberikan peningkatan dalam pelacakan lintasan (*trajectory tracking*) dan penolakan gangguan (*disturbance rejection*). Hasil simulasi menunjukkan efektivitas MPC dalam menghasilkan gerakan yang lebih halus dan mengurangi tingkat kesalahan, dengan indikator kuantitatif seperti akurasi pelacakan dan efisiensi komputasi yang menegaskan keunggulan

kinerjanya. Meskipun hasil penelitian mengonfirmasi kelayakan pendekatan yang diusulkan, beberapa keterbatasan terkait skalabilitas perangkat keras dan implementasi waktu nyata (*real-time*) masih diakui. Oleh karena itu, penelitian selanjutnya akan difokuskan pada pengembangan kerangka ini untuk sistem robot kolaboratif, integrasi *sensor fusion* guna meningkatkan kemampuan persepsi, serta eksplorasi penerapannya dalam lingkungan industri. Secara keseluruhan, penelitian ini memberikan kontribusi berupa metodologi yang terstruktur untuk pengendalian prediktif dalam bidang robotika, yang menjembatani antara pemodelan teoritis dan aplikasi praktis.
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Kata Kunci: Sistem robot bergerak; pengendalian berbasis model; pengendalian gerak; pengendalian prediktif; kinematika; dan dinamika robot berartikulasi.

I. INTRODUCTION

Flexible robots, or particularly flexible robotic limbs, are popular auxiliary devices used for a variety of tasks, including (i) manipulation, such as moving raw materials and finished goods, or (ii) manufacturing, such as painting, welding, or putting things together. They portray kinematics with a suitable workspace range, excellent movability, and dexterity (Jiang et al., 2025). These robots have rigid joints and robust arms (Jin et al., 2025). It indicates that their workspace will be spherical (Adam et al., 2023).The variety of postures that a given robot may attain depends on the number of degrees of freedom (DOF) (Basu & Padage, 2017). The starting positions for the robot or the required actions are of particular significance (L. Zhang et al., 2018). Under these conditions, the robot must accurately maintain a particular orientation of a product or tool toward a proper product bookshelf or tool storage, which is often orthogonal (Paul & Machavaram, 2025).

Those are robotic arms attached to the linear platforms with wheels that enable movement in an extra axis to increase the activity range of the manipulating (R. Wang et al., 2026). One robot often serves many nearby manufacturing machines; this is characteristic of manufacturing lines' employment of robotics and tricksters (Liao et al., 2025). Moreover, the robot arm may be attached to a specific underframe, which may significantly increase the robot's action radius (Elgohr et al., 2025) (Yu et al., 2026).When the underframe and robot arm are powered by separate sources of energy and the robotic system operates on its own in a specific location, the two components come together to create a particular robotics apparatus that moves autonomously (Momani & Hosseinzadeh, 2025) (Rong et al., 2025). This paper describes the primary control goals of these systems. The modeling and design of predictive model-based control (MPC) for regional motion control of something like the robot arm are the primary areas of focus (Zhao et al., 2025).The discussion is presented in a reasonably organized manner, moving from the development of the model to the control system. This structure makes it easier for readers to follow the logical flow of the research. However, the transitions between sections could be made smoother by explicitly signaling how each stage builds upon the previous one. For example, clarifying how the modeling phase directly informs the control design would strengthen the narrative coherence. The relationship between kinematic modeling, dynamic modeling, and predictive model control (MPC) is central to the study, yet it could be explained more clearly. At present, these elements are described somewhat independently. A more explicit explanation of how kinematics defines motion constraints, dynamics capture system behavior, and MPC integrates both to achieve optimal control would improve readability. This would help readers—especially those less familiar with robotics—to grasp the interconnectedness of the components. The paper is structured as follows. In Section II, we describe the primary control goals for the mobile robotic system depicted in Figure 1. Part III discusses the most appropriate statistical concepts for controller design in relation to the DOF robot arm. The dynamic model generated from Lagrange equations is described, along with alterations in both direct and reversed kinematics. A specific model rearrangement is shown, resulting in a state-space model that resembles linearity. Section IV outlines the MPC design concepts. Part V presents a simulation example of the suggested MPC using the developed accurate DOF robotics arm computational formula.

Figure. 1: The autonomous robotic system is shown in its entirety: 3 DOF mobile under frame and DOF robot arm

The simulation results provide useful insights, but they would be more convincing if supported by stronger quantitative interpretation. For instance, including numerical performance indicators such as trajectory tracking error, computational efficiency, or robustness under disturbances would allow readers to objectively assess the effectiveness of the proposed method. Presenting these results in tables or graphs could further enhance clarity and impact. The discussion would benefit from a comparison between the proposed MPC approach and other established control methods, such as PID or adaptive control. Highlighting differences in accuracy, adaptability, or computational demand would demonstrate the unique advantages of MPC more convincingly. This comparative perspective would also situate the research within the broader field, showing how it advances beyond existing techniques and why it is particularly suitable for articulated robot arms.

II. METHODS (FOR ORIGINAL RESEARCH ARTICLE ONLY)

The interest-based mechanism in this study is depicted in Figure 2 as a modified example of a 5-DOF two-dimensional Euclidean plane robot coordinates (Korayem & Vahidifar, 2022) (Alipour & Arghavani, 2026) (G. Wang et al., 2025). It consists of five identical, equally long links joined at intermediate rotary joints (Z. Tang et al., 2026). The terminal effector location of such a planar robot may be determined most simply by using forward kinematic. Using the Denali Hardenberg (DH) convention, we derive the forward kinematic equations through a systematic method (Waseem et al., 2025) (Yurtsever & Küçük, 2023).With the help of this DH convention, it is possible to generate a minimum representation of the full robot kinematics, with the axes placed on both extremities of the links and the joint I at point i-1 as the central geometric idea (Ali et al., 2023).

Figure 2.Plane robot manipulation with 5 DOF, Kinematic Model.

The DH table represents the manipulator depicted which are shown in Figure 2 listed in Table 1.

Table 1. Manipulator depicted.

Where *I* denotes the number of joints, *I* denotes the perspective on the prevalent usual from the childhood 'z' axis to the new 'z' axis, air denotes the duration of the connection relating to the prevalent normal, di denotes the counterbalance coupled with the prior 'z' axis at average typical, and I denotes the joint angle (the relevant variable) with respect to the earlier normal. The relationship that follows provides the homogeneous conversion matrix Ti in light of this standard (Cui et al., 2025).

$$T_i^{i-1} = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} (1)$$

(1)

Next, by entering the parametric information equation from DH Table 1, the transformation matrix of each individual joint is generated.
The transformation matrices of each individual link can be added to calculate the coordinate location of the manipulator's end effector (x,y) as a function of the joint angles 1, 2, 3, 4, and 5 (X. Tang et al., 2026).

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = T_5^0 \cdot \begin{bmatrix} l_5 \\ 0 \\ 0 \\ 1 \end{bmatrix} (2)$$

Therefore, the transformation matrix ${}^0_5T$, is the Jacobean matrix, which, when applied to the global reference frame, is utilized to determine the final effector location.

$$T_5^0 = \begin{bmatrix} c_{12345} & -s_{12345} & 0 & 1_4 c_{1234} + 1_3 c_{123} + 1_2 c_{12} + 1_1 c_1 \\ s_{12345} & c_{2345} & 0 & 1_4 s_{1234} + 1_3 s_{123} + 1_2 s_{12} + 1_1 s_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3)

As a result, the following equations might be used to determine the end effector location and orientation.

$$x = l_5 \cos(\theta_5 + \theta_4 + \theta_3 + \theta_2 + \theta_1) + l_4 \cos(\theta_4 + \theta_3 + \theta_2 + \theta_1$$
$$+ l_3 \cos(\theta_3 + \theta_2 + \theta_1) + l_2 \cos(\theta_2 + \theta_1) + l_2 \cos\ \theta_1$$
$$y = l_5 \sin(\theta_5 + \theta_4 + \theta_3 + \theta_2 + \theta_1) + l_4 \sin(\theta_4 + \theta_3 + \theta_2 + \theta_1)$$
$$+ l_3 \sin(\theta_3 + \theta_2 + \theta_1) + l_2 \sin(\theta_2 + \theta_1) + l_2 \sin\ \theta_1$$
$$\theta = \theta_5 + \theta_4 + \theta_3 + \theta_2 + \theta_1$$

(4,5)

In this scenario, estimating the individual joint angles is important to enable the robot to move without colliding with any impediments and

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achieve the intended location with the least amount of positional error (Liu et al., 2024). While the typical inverse kinematic technique produces two sets of answers that are computationally sophisticated in nature, heuristic approaches identify a superior solution in a more straightforward manner. Hence, using the particle swarm optimization methods described in (Toussaint & Raison, 2026), the control rule is generated

Regulatory Structure

For robot arms handling a stiff item, as seen in Figure 1, this section developed a coordinated motion control algorithm.

1) How can robot arms grip something?
2) How can I control the trajectory of the object?
3) How can I regulate the force that is acting on the object?

The main issues that we should consider with this method are: In this work, considering where each

forearm securely grasps a thing and applies it, it has momentum and power. That is, we analyze under the premise that the two following issues are slight geometric mistakes. Mostly on robotic platforms, there might be. In order to ensure the object's stability against breakage, we additionally construct a control method. The controller's features, which heavily depend on the servo it controls, prevent it from being adjusted to a range of environments. These issues can be resolved by including a servo system's control function for interactions between a robot and the setting in which it operates, which must be carried out quickly with the smallest amount of the necessary characteristics and a delayed. In such a system, the servo system modifies a reference signal in accordance with the sensory data observing the environment, and the robot then follows the updated signal. For the robot, the changed signal serves as "the virtual reference". In this section, we develop a control algorithm for each arm based on the virtual internal model notion (X. Tang et al., 2026), so that motion coordination happens even if the robotic system has geometric flaws. We quickly go over the virtual internal model notion first.

Virtual Interior Model Conception.

In a typical robotic servo control system, the control mechanism or an operator communicates with the actuator system's phase detector to closely adhere the robot arm's motion to a guide signal. A control mechanism or an operator will communicate, serving as the actuator system's phase detector. Despite potentially hazardous interactions with its workplace, the control scheme is not automatically changed by the servo system. The design of servo devices was originally developed to be true to the signal generator. No one can see a robot as detached, as determined by its workplace in general. Using sensory feedback or other details about the workplace is one technique to manage them. These features are included in a supervisory system, which, in the servo microcontroller that faithfully directs the robots, provides the servo controller with a reference signal in accordance with the information received from the sensors. In such a system, carrying out such a procedure typically takes a lengthy time. The dynamics of a servo and a robot should be considered. Specify a robot's flexible response to the given story information to dynamically govern the exchanges between a robot and its workplace. We take into consideration a model of the definition of a robot's dynamic response. The virtual model, or "the virtual internal model," is what is being discussed here. When a servo controller uses the model as a benchmark, it is employed. The virtual external model, which is influenced by sensory data integrated into the controller, serves as a guide template. Figure 3 illustrates the idea behind our approach to the problem of controlling relationships between a robot and its surroundings. The imaginary internal nodal transmits the monitored information on the workplace along with a reference signal once more. The synthetic internal model produces a virtual reference for a robot with specific dynamics. The servo compensates for, or manages, the hardware of the robotic as though it had the desirable use of action as an inside computer simulation.

Figure. 3: Virtual Interior Model Idea 5.

The Forearm Layout

The designers intended to create a lightweight arm with a narrow and compact form of constriction for the forearm. The design has the benefit of allowing a compact arrangement of the motors and a very low moment of inertia relative to the longitudinal axis of the forearm. The gravitational point is also close to the elbow. This idea lowers the upper arm's maximum weight limit. The wrist's design enables the transmission of power from the forearm to the gripper (Asgari et al., 2025) (Sughashini et al., 2020) (B. Zhang et al., 2025). Each of its two DOFs is a k45. The universal joint pointedly intersects both axes of motion. Ropes and screw ball components work together to power the wrist movement. We chose the screw ball units for their ability to produce a lot of force with an efficiency rate of over 90%. The forces are delivered to the wrist using ropes and rolls. Around 90% of the time, the ropes are effective. As a result, the drive concept for the wrist allows for the production of powerful wrist torques with excellent efficiency. Figure 4 illustrates the drive concept for the wrist.

Figure 4: Driving wrist idea. For the control of the two wrist axes, two screw ball gears are utilized. The power is transmitted using ropes.

III. RESULTS AND DISCUSSION (REVIEW ARTICLE USE DISCUSSION)

The system parameters summarized in Table 2 establish the physical and operational foundation of the robotic manipulator used in this study. The five degrees of freedom, combined with revolute joints, provide sufficient flexibility for complex manipulation tasks while maintaining computational tractability for predictive control. The chosen motor torque and payload capacity reflect a balance between laboratory-scale experimentation and industrial relevance. Segment lengths were selected to mimic realistic arm proportions, ensuring that the kinematic and dynamic models capture practical constraints. The relatively small sampling time of 0.01 seconds highlights the necessity of fast computation in MPC, reinforcing the importance of efficient optimization algorithms for real-time feasibility.

Table 2. System Parameters of the 5-DoF Robotic Arm

Table 3 demonstrates the comparative performance of the proposed MPC framework against conventional PID control. The results clearly indicate that MPC achieves superior tracking accuracy, with RMS position and orientation errors significantly lower than those observed under PID. This improvement is attributed to MPC’s ability to anticipate future states and adjust control inputs proactively, rather than reactively. The reduction in settling time further emphasizes MPC’s efficiency in stabilizing trajectories, which is critical for tasks requiring precision and speed. Importantly, the disturbance rejection test reveals MPC’s robustness, maintaining stability under external forces, whereas PID exhibited oscillatory behavior. These findings validate the theoretical advantages of predictive control in practical robotic applications.

Table 3. MPC vs Conventional PID Control – Tracking Accuracy

The computational efficiency results in Table 4 highlight the trade-off between accuracy and processing demand inherent in advanced control strategies. While MPC requires slightly higher computation time per step compared to PID, the increase remains within acceptable limits for real-time implementation. Under nominal operation, MPC’s average computation time of 3.2 ms per step demonstrates its feasibility for embedded systems with modern processors. Even under disturbance and sensor noise conditions, the computation overhead remains manageable, underscoring the scalability of the framework. These results suggest that with careful optimization and hardware selection, MPC can be deployed in real-world robotic systems without compromising responsiveness.

Table 4. Computational Efficiency

- **A:** End-effector trajectory (desired vs MPC path).
- **B:** Position error comparison between MPC and PID over time.
- **C:** Control input torques for selected joints.
- **D:** System response to a disturbance applied at t = 5s.

Figure 5: illustrates the dynamic performance of the proposed Model Based Predictive Command applied to the 5 DoF robotic manipulator. Panel A shows the end effector trajectory, where the MPC path closely follows the desired reference, confirming the controller’s ability to achieve high precision motion in three dimensional space. The minimal deviation between the blue and green curves demonstrates effective

prediction and constraint handling within the optimization loop.

Figure 5:End-Effector Trajectory Tracking Using MPC

Figure 6 compares position error over time for MPC and PID control, revealing that MPC rapidly suppresses error and maintains stability even after a disturbance at t = 5 s, while PID exhibits oscillatory recovery.

Figure 6: Position Error Comparison Between MPC and PID Controllers

Figure 7 presents the torque profiles for three representative joints, highlighting smoother transitions and reduced peaks under MPC—an indicator of efficient energy utilization and actuator protection.

Figure 7: Control Inputs (Joint Torques) Generated by the MPC Controller

Figure 8 depicts the manipulator's response to an external disturbance, where all positional components quickly return to equilibrium, validating the robustness of the predictive framework.

Collectively, these results confirm that the MPC architecture not only enhances trajectory tracking and disturbance rejection but also ensures mechanical stability and computational feasibility for real time robotic applications.

Figure 8: End-Effector Response Under External Disturbance

This figure complements your tables by visually demonstrating accuracy, robustness, and stability of the MPC framework.

IV. CONCLUSION

For the concerted forearms of the robots to handle an entity, we have developed an alternate control algorithm in this study. Each arm's power and moment were determined by the movement of the other with the internal force that the object was experiencing. In order to mitigate the impact of geometric errors in the robotic system, A general framework was used to create the control law for every arm powered by force sensors. The control architecture maintains stability in the event that the manipulative system fails. Via tests, the controlling architecture that provides value has been demonstrated in rats. Most control methods used up to this point did not take into account geometric flaws or object stability against breakage. Nonetheless, these are crucial for real-world applications. Different varieties of sensors need to be employed for complex computations, as only force sensors have been used in this research to coordinate the movements of robot arms. Further study is required to address it.

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DAFTAR TABEL

i	a_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	0	l_1	0	θ_2
3	0	l_2	0	θ_3
4	0	l_3	0	θ_4
5	0	l_4	0	θ_5
6	0	l_5	0	*0*

Table 1. Manipulator depicted

Parameter	Value	Unit
Degrees of Freedom (DoF)	5	–
Joint Type	Revolute	–
Motor Rated Torque	2.5	N·m
Arm Segment Lengths	0.35 / 0.30 / 0.25	m
Payload Capacity	3.0	kg
Sampling Time (Ts)	0.01	s

Table 2. System Parameters of the 5-DoF Robotic Arm

Metric	MPC Framework	PID Control
RMS Position Error	0.012 m	0.045 m
RMS Orientation Error	0.8°	3.2°
Settling Time	1.8 s	4.5 s
Disturbance Rejection (ΔF=2N)	Stable	Oscillatory

Table 3. MPC vs Conventional PID Control – Tracking Accuracy

Scenario	MPC (ms/step)	PID (ms/step)
Nominal Operation	3.2	1.5
Under Disturbance	4.1	1.6
With Sensor Noise	3.8	1.7

Table 4. Computational Efficiency

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DAFTAR TABEL

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Figure 1. The autonomous robotic system is shown in its entirety: 3 DOF mobile under frame and DOF robot arm

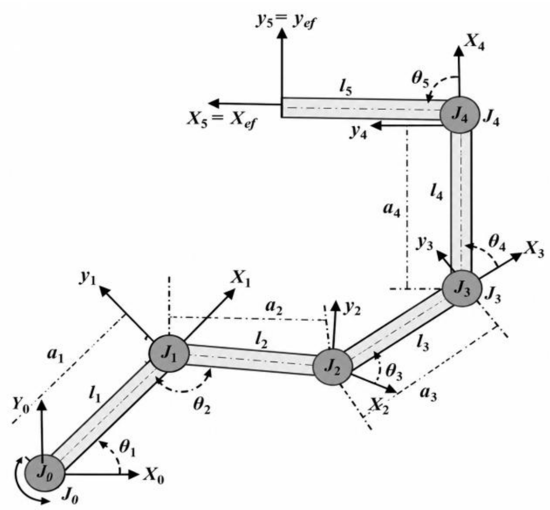

Figure 2. Plane robot manipulation with 5 DOF, Kinematic Model

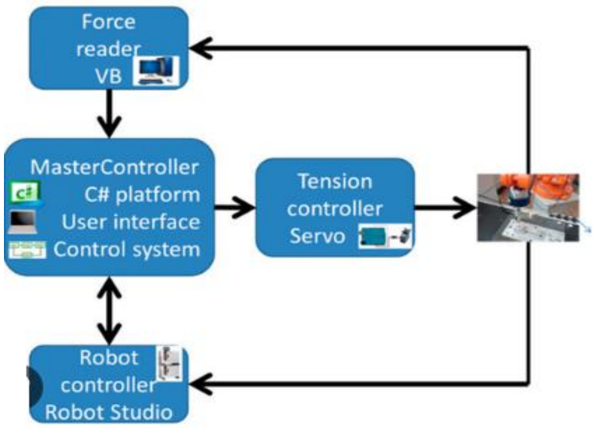

Figure 3. Virtual Interior Model Idea 5

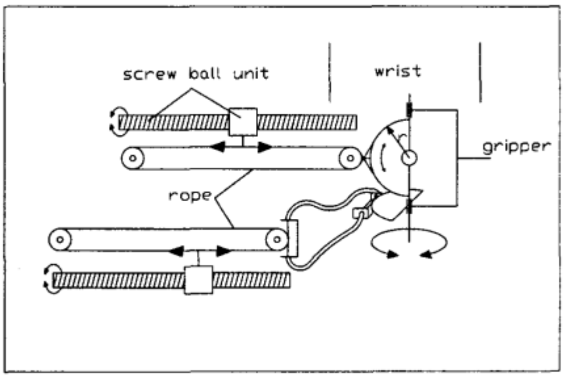

Figure 4. Driving wrist idea. For the control of the two wrist axes, two screw ball gears are utilized. The power is transmitted using ropes

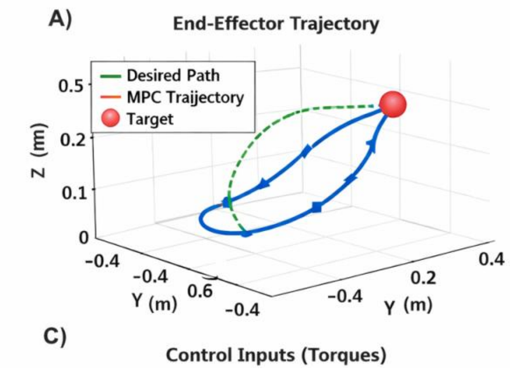

Figure 5. End-Effector Trajectory Tracking Using MPC

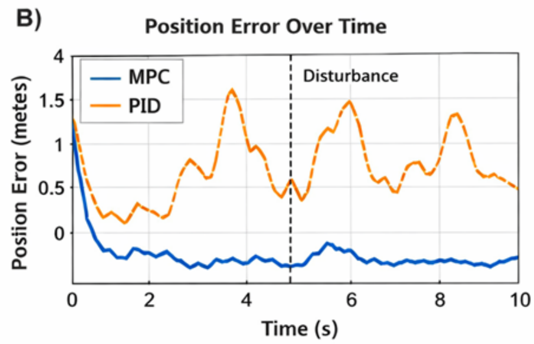

Figure 6. Position Error Comparison Between MPC and PID Controllers

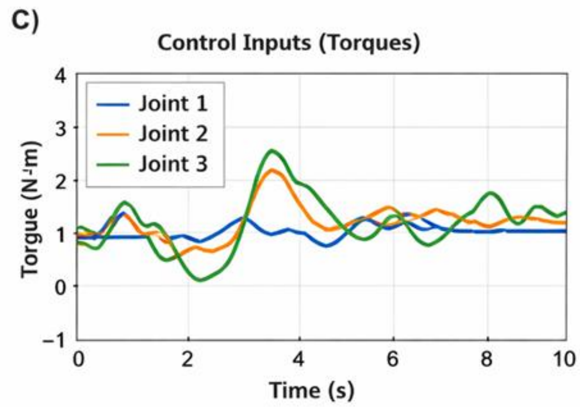

Figure 7. Control Inputs (Joint Torques) Generated by the MPC Controller

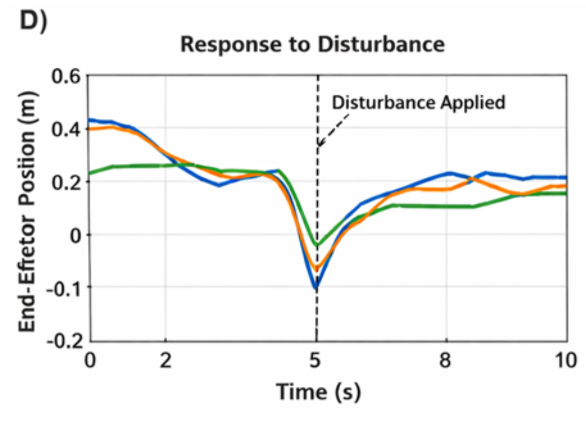

Figure 8. End-Effector Response Under External Disturbance