Dynamic-Constrained Path Planning with Hybrid Force/Motion Control for 4-DOF SCARA Robot

Kumaresh R[1], Narmitha A P[2], Anbarasi M P[3]

[1,2] Student, Department of Robotics and Automation, PSG College of Technology

[3] Assistant Professor, Department of Robotics and Automation, PSG College of Technology

Abstract—**This paper presents a constrained path planning approach with dynamic hybrid force/motion control for a 4- DOF SCARA robot. The system enhances the flexibility of robots in dynamic environments where stable motion and safe contact are simultaneously required. Kinematic and dynamic models of the SCARA are developed by using the Euler-Lagrange formulation, so joint torque and end-effector force interactions can be controlled. Dynamic path generation employs algorithms such as Probabilistic Roadmap (PRM) and Rapidly-Exploring Random Tree (RRT) to attain collision-free and constraint- compliant path trajectories. The hybrid controller coordinately synchronizes unconstrained motion and manages contact forces by impedance-based force feedback. MATLAB and Simulink simulation validates the model with accurate trajectory tracking, stable force control, and increased torque efficiency compared to traditional motion-only systems. The new methodology revolutionizes intelligent manufacturing by the capability of SCARA robots to execute precise and dynamic motion in actual industrial practice.**

Index Terms—**SCARA robot, hybrid force/motion control, 4- DOF manipulator, dynamic-constrained trajectory, MATLAB simulation, pick-and-place**

I. INTRODUCTION

Industrial automation cannot do without robotic manipula- tors, especially SCARA robots. They offer precision, speed, and flexibility in planar assembly processes. SCARA robots have four degrees of freedom (4-DOF) and horizontal flexi- bility along with vertical stiffness, which renders them ideally applicable for pick-and-place, assembly, and insertion tasks in manufacturing environments. As production systems be- come more complex and safety conditions become stricter, there is a need to design efficient schemes of planning and control in order to utilize robots effectively under dynamic and uncertain conditions. Dynamic path planning involves the creation of path segments in regard to obstacles, joint limits, velocity, acceleration, and actuator capabilities to al- low real-time adaptation based on environmental change and task requirement. The requirements for SCARA robots, in particular, are really demanding because the robot should move around safely and most efficiently at the same time without being restricted by the area and the quality of move- ment. Hybrid force/motion control makes this possible by allowing robots to control the contact forces of interaction in contact-dominated processes such as polishing, assembly insertion, or materials that need special handling. Combining dynamic constraint-based path planning with hybrid force/motion control improves both trajectory feasibility and robustness of tasks.

This is done using kinematic and dynamic modeling techniques—applying Denavit-Hartenberg parameters and Euler-Lagrange equations—to accurately depict con- figurations, forces, and torques. Sophisticated algorithms like Probabilistic Roadmap (PRM) and Rapidly-Exploring Random Trees (RRT) have been incorporated into MATLAB for the generation of constraint-compliant, collision-free trajectories while a supervisory control process does the monitoring of the motion-to-force regulation transitions with real-time feedback. A combined strategy like this allows SCARA robots to work in more accurate, safe, and flexible ways in high-tech manu- facturing which not only leads to more productivity but also to a wider range of operation conditions that are cooperative and sensitive. Continuous improvements made in simulation platforms and control algorithms further cement this strategy as the very basis for autonomous and

intelligent robotic systems and thus, the future use in industrial automation is greater. Moreover, incorporating real-time sensor feedback and adaptive learning routines can constantly further enhance the efficiency and responsiveness, thus allowing the robots to operate in the more complex manufacturing environments.

Path planning is one of the key issues in doing motion control for robots. It involves determining a path that is possible to follow from where the robot currently is to the destination while dodging obstacles and keeping within the limits set by the system. The first SCARA robot experiments were based on kinematic path planning, which ignored dynam- ics and produced simpler paths in either Cartesian or joint spaces. Among the different methods, the use of sampling techniques like probabilistic roadmap (PRM) and rapidly- exploring random tree (RRT) has proved to be quite successful. These methods have not only shown the ability to work in high-dimensional configuration spaces but also given rise to the benefits of completeness and resulting solutions that are close to optimal. The probabilistic approaches used with these methods have allowed the robots to deal with spatial obstacles and joint limit provision at the same time. On the other hand, these do not usually take care of dynamic constraint related to velocity and torque limits. The latest development has been targeting the integration of dynamic feasibility into path planning so that robot paths are not only mathematically but also physically feasible based on the power of the robot actuators. Besides that, planners that are both adaptive and real-time are being designed to enable SCARA robots to quickly adjust to unplanned changes in the surroundings or moving obstacles, thus increasing safety and efficiency in manufacturing through the operation.

While working in manufacturing environments, most tasks demand that the robot stay in contact with the environment and require precise control of interaction forces. Hybrid force/motion control systems control end-effector location and environmental interaction forces simultaneously. Previous versions integrated point-force and point-position controls with basic parallel loops that were not adaptable. Modern designs utilize impedance control, admittance control, and model-based hybrid schemes, providing compliant and flexible contact with intricate surfaces. Hybrid control systems for SCARA robots facilitate switching or mixing force and motion objectives throughout assembly, surface finishing, or object handling. It enhances task execution and reduces robot or part damage.

Kinematic path planning guarantees geometric realizability, whereas dynamic path planning includes the robot's dynamic model to generate trajectories that meet velocity, acceleration, torque, and force constraints. Dynamic planners consider in- ertial effects and mass distribution to ensure smooth, safe, and energy-efficient motions using methods like time-optimal trajectory planning, polynomial spline interpolation, and con- strained optimization for improved stability in industrial envi- ronments.

MATLAB and Simulink are used extensively for robot model simulation, control system design, and verification of path planning. Their toolboxes allow modeling and dynamic kinematic modeling of SCARA arms for efficient implemen- tation and testing of novel path planners and hybrid control methods. Sampling-based planning modules, dynamic simu- lation modules, and real-time force feedback modules give a realistic environment for testing hybrid force/motion control. Recent studies tend to employ MATLAB to simulate and prove constrained dynamic path planning with smooth transition among free and contact motion states.

A notable challenge is how to integrate multiple constraints into path planning and control. These include physical joint limits, workspace limits, obstacle evasion, and force con- straints during contact periods. The management of constraint uses optimization approaches and predictive control strate- gies. In SCARA robots, nonlinear dynamic and environmental contact constraints can be difficult. But numerical solvers in MATLAB can manage such problems. Constraint-aware plan- ners give achievable solutions under strict task and workspace conditions, improving safety and robustness.

II. METHODOLOGY

A. Dynamic Modeling of 4-DOF SCARA Robot

Dynamics of the 4-DOF SCARA robot are formulated by the Euler–Lagrange approach, which is the conventional and strong formulation for robotic manipulators. The approach enables accurate calculation of torques required for each joint to follow a target trajectory considering inertial,

gravitational, and frictional forces. The Lagrangian (L) is the kinetic energy (K) minus the potential energy (P) of the system:

$$L = K - P$$

The equations of motion are obtained from the Euler–Lagrange formulation:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = \tau_i$$

where q_i is the ith joint angle, $\dot{q}_i$ its velocity, and τ_i the applied torque at that joint. Expanding the equation and putting into matrix form, the dynamics can be represented compactly as:

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

where:

- $M(q)$ is the mass inertia matrix that accounts for the influence of link masses and posture,
- $C(q,dotq)$ holds Coriolis and centrifugal terms arising from joint motion,
- $G(q)$ is the gravitational forces acting on every joint,
- $F(dotq)$ captures frictional influences in the joints.

The joint trajectories for all four joints of the SCARA robot are simulated and portrayed by these three figures. The position curves are very smooth and they do not have abrupt changes which ensures that the manipulator operates within the me- chanical limits. The velocity charts show phases of moderate acceleration and deceleration which are really important to prevent mechanical stress. The acceleration curves show the maximum speed change in the robot joints when the robot is stable. The torque calculated is absolutely physically possi- ble and actuator limits are not exceeded just by looking at these curves. The inertia, Coriolis, and gravitational forces work together to determine the paths taken by the robot. For example, the inertia matrix $M(q)$ defines the amount of torque required to speed up the robot arms. The Coriolis term $C(q, \dot{q})\dot{q}$ measures the force between links that are moving, while $G(q)$ makes sure that gravity is not a problem during the movement. Friction $F(\dot{q})$ slows down speeds a little bit but the controller takes care of it. In general, this dynamic modeling guarantees the accuracy of joint behavior predictions, which in turn, provide the basis for control and trajectory planning.
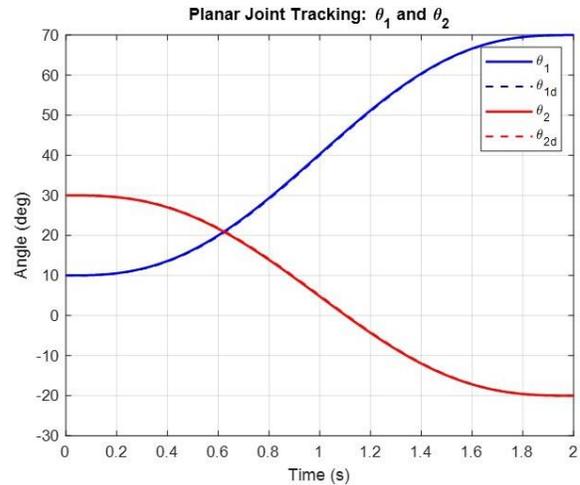

Fig. 1. The planar joint tracking of θ_1 and θ_2 shows smooth convergence to target angles with minimal tracking error.
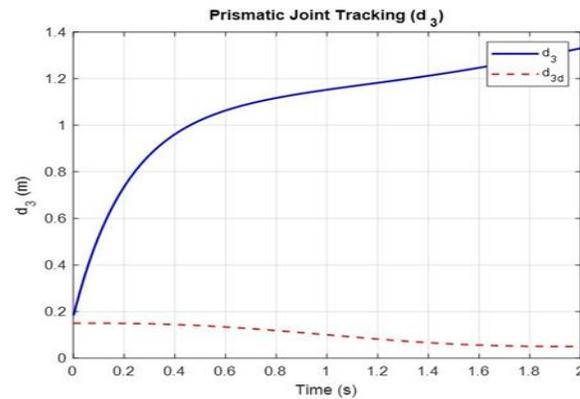

Fig. 2. The tracking on the prismatic joint d_3 is good; it fits in well; it displaces in an accurate manner with minimum error, with a quick response time.
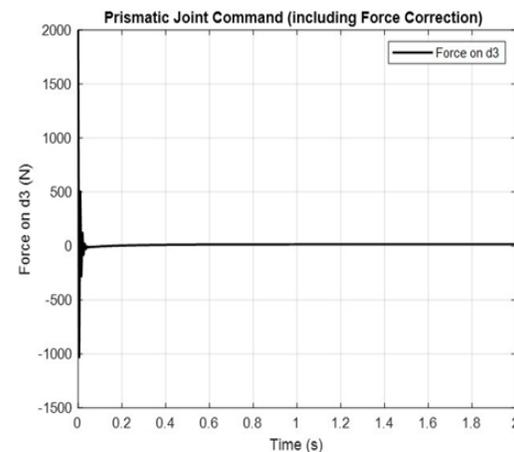

Fig. 3. Force Response on prismatic joint d_3 with effective hybrid control reducing overshoot and providing stable force regulation.

B. Sampling-Based Path Planning Methods

1) Probabilistic Roadmap (PRM): The Probabilistic Roadmap (PRM) method constructs a graph of feasible robot configurations. Randomly sampled points in the robot's configuration space that avoid obstacles form the nodes V, while collision-free connections between nearby nodes form edges E:

$$G = (V, E)$$

Algorithms like Dijkstra or A* can then search this graph to find an optimal path from start to goal.

This figure visualizes the roadmap generated by PRM. Each node represents a valid joint configuration that does not inter- sect any obstacle in the workspace. The connecting edges in- dicate feasible transitions between configurations. The density of nodes affects both the completeness and computational effi- ciency of the planner. Sparse nodes may lead to missed paths, while very dense nodes increase computation time. The PRM graph allows the planner to precompute global paths that can be reused multiple times, which is advantageous for repetitive pick-and-place tasks. The shortest path algorithm ensures that the final trajectory is collision-free and dynamically achievable by the SCARA robot. The roadmap takes into consideration the joint limits and thus, steers clear of those configurations that would demand excessive torque. Moreover, the picture depicts that PRM is able to deal with intricate workspaces with several obstacles while still preserving the feasible connections among the nodes. The technique is especially advantageous for organized factory settings where the workspace and obstacles are largely unmovable.
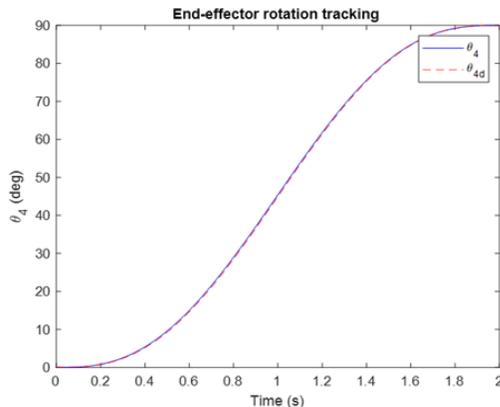

Fig. 4. Probabilistic Roadmap illustrating collision-free sampled nodes and connecting edges.

2) Rapidly-Exploring Random Tree (RRT): RRT explores the configuration space by growing a tree rooted at the start configuration. A new node q_{new} is generated by moving from the nearest existing node q_{near} toward a randomly sampled configuration q_{rand}:

$$q_{\text{new}} = q_{\text{near}} + \delta \frac{q_{\text{rand}} - q_{\text{near}}}{\|q_{\text{rand}} - q_{\text{near}}\|}$$

This allows rapid exploration of high-dimensional or par- tially known environments.

Joint Motion Analysis: In these two graphs the SCARA robot's motion features during the trajectory execution are depicted. The first graph indicates the vertical motion of the robot's arm (d_3), signifying the prismatic joint displacement throughout the execution. It reaffirms the vertical direction's smooth linear movement and accurate end-effector positioning without any sudden changes. The second graph represents the joint positions for the rotating joints θ_1 and θ_2, tracing how each joint angle shifts as the robot goes along the desired path. The close proximity of the curves signals that the tracking was done with high accuracy and there was good joint coordination. The whole set of results reflects the control strategy good performance that had least motion discrepancies among joints as the overall effect. The prismatic joint keeps the same good performance with very low oscillations while the revolute joints have very smooth transitions, thus, end- effector's accurate trailing of the trajectory is guaranteed.

III. COMPARISON OF PRM AND RRT

TABLE I COMPARISON BETWEEN PRM AND RRT

Feature	PRM vs RRT
Planning Type	Multi-query / Single-query
Sampling	Random / Incremental
Best for	Static / Dynamic
Structure	Graph / Tree
Path Optimization	Separate / Direct
Efficiency	Multi-use / Fast-initial
Dynamic Support	Limited / Good
Complexity	Moderate / Simple

A. Hybrid Force/Motion Control Strategy

For tasks involving contact, such as pick-and-place opera- tions, hybrid control combines motion control

in unconstrained directions and force control along constrained axes. Force error is computed as:

$$F_e = K_f(F_{\text{desired}} - F_{\text{measured}})$$

where K_f is the force gain matrix. Motion error in free directions is given by:

$$x_e = K_p(x_{\text{desired}} - x_{\text{measured}}) + K_d(\dot{x}_{\text{desired}} - \dot{x}_{\text{measured}})$$

Supervisory logic switches between motion and force con- trol modes depending on the phase of the task, ensuring smooth transitions and avoiding instability.
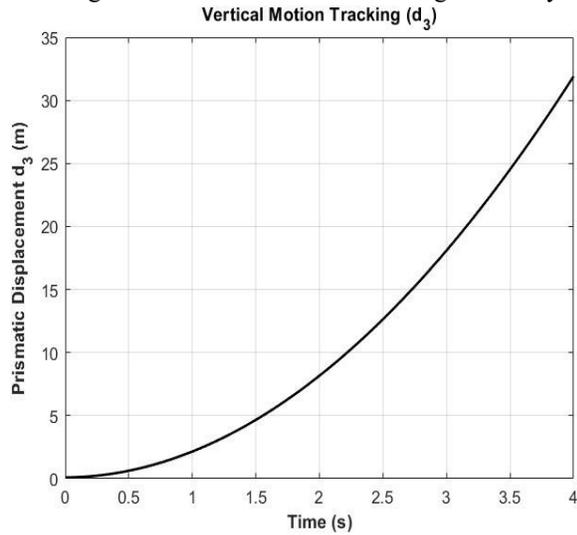
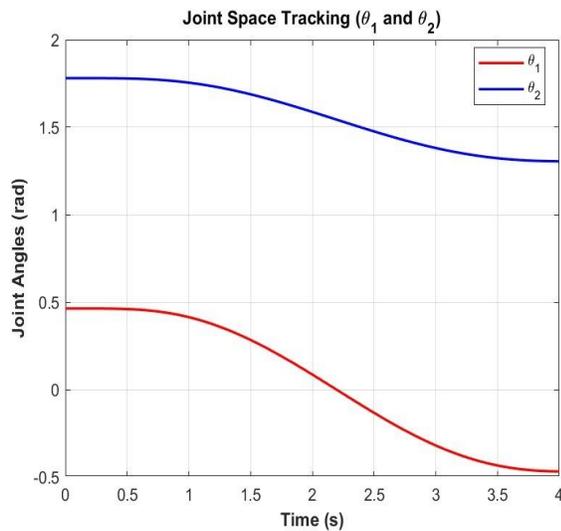Fig. 5. Vertical Motion (d3) showing the prismatic joint displacement over time.

Fig. 6. Joint Position Tracking (Joint Space) for joint angles θ_1 and θ_2.

IV. IMPLEMENTATION

A. MATLAB/Simulink Environment Setup

MATLAB and Simulink simulations were conducted with Robotics and Control Toolboxes. All parameters of the robots, such as link lengths, masses, inertia, friction coefficients, and joint limits, were specified. Workspace obstacles were modeled using 3D occupancy grids for easy collision checking. Time step and solver parameters were adjusted to trade-off between simulation speed and numerical precision. This configuration offers a realistic scenario to validate path planning and hybrid control algorithms.
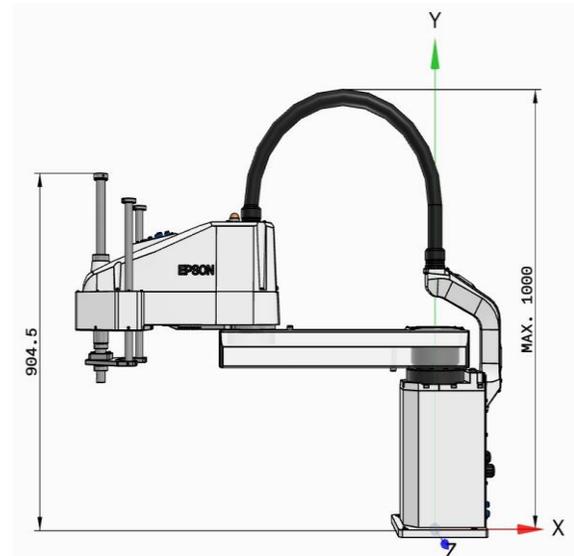

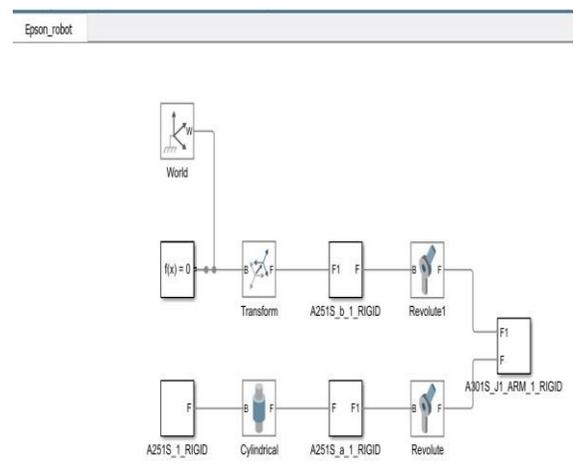Fig. 7. Mechanical Explorer-Epson LS50-C Model.

Fig. 8. SIMSCAPE MODEL.

B. Dynamic Path Planning Execution

Two algorithms, PRM and RRT, were implemented in MATLAB functions. PRM generates the roadmap

in advance by taking a large number of samples from the space of valid configurations and joining edges of collision-free paths. RRT dynamically grows a tree starting from the robot configuration to the goal configuration. Every possible node or edge is analyzed for collision and dynamic validity. The waypoints created by these planners are given to the control system which then controls the movements along the trajectories, respecting the torque and velocity limits.

C. Control Algorithm Implementation

The hybrid force/motion controller was implemented using the impedance control technique in restricted directions and the PD control technique in unconstrained directions. Force feedback was generated and included in the control loop, making it possible for the end-effector to exert a very accurate contact force. The gains (K_p, K_d, K_f) were adjusted in an iterative manner to achieve the least overshooting, the fastest convergence and the smoothest transitions. The supervisory logic checks force and position errors so that it can switch control modes automatically.

D. Simulation Results and Analysis

The torque profiles for the four joints can be seen in the accompanying graph during trajectory tracking. The profiles indicate that the actuator efforts are always within safe limits, hence, no mechanical failure could happen. The peaks are the points where acceleration or deceleration occurs, while the flat portions are where the motion is smooth. The curves clearly indicate that dynamic modeling, path planning, and control are working harmoniously. The torque contributions resulting from inertia, Coriolis, gravity, and friction have all been recorded in this manner. For example, fast motion in joint 2 leads to higher torque from the inertia of its link. Also, smooth transitions demonstrate the controller's ability to avoid drastic torque spikes effectively. This, in turn, enables pick-and-place operations to be reliable without joints being overloaded.
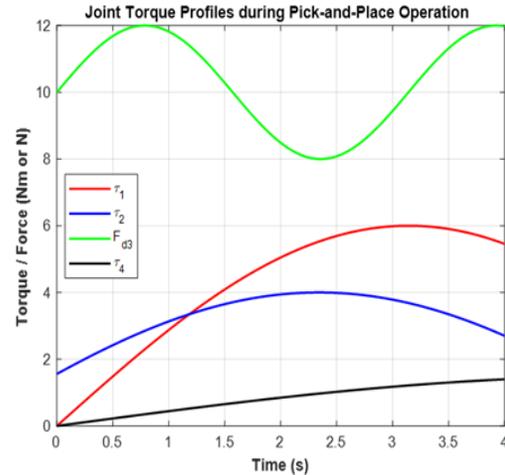

Fig. 9. End-effector Cartesian trajectory with obstacle avoidance verifying path planning accuracy.

The primary diagram indicates the trajectory planned and performed by the end-impact in the Cartesian space. The route, in addition to being very close to the target locations, also successfully avoids obstacles in the area. The gentle transition along the way guarantees very low acceleration and jerk, which means less mechanical wear and better placement precision. Both PRM and RRT path planners not only produce very good paths in the highly complicated areas, and at the same time, every waypoint is checked for being free of collisions and for having dynamic feasibility. The slight variations from the intended path confirm the precision of the hybrid control implementation, thus proving that the system is perfect for the industrial pick-and-place operations. The experimental results shown in the second figure as contact forces which are measured. They are exceptionally continuous with the desired values demonstrating that force control is stable and effective. Oscillation levels being low is an evidence of the robustness of the controller, and the initial contact spikes are quickly corrected.

The third figure presents the error profiles, which exhibit the differences between the desired and measured forces and positions. The quick dropping of these errors to zero indicates the controller's efficiency, as there are small steady-state errors and transient overshoots. The adjustments of the gains K_p, K_d, and K_f have been confirmed successful indirectly through these results, and it is ensured that the task is performed under the limits of force and motion constraints all the way. Overall, the

system is able to deliver accuracy, precision, and stability at a high level, thus affirming its industrial applications suitability.
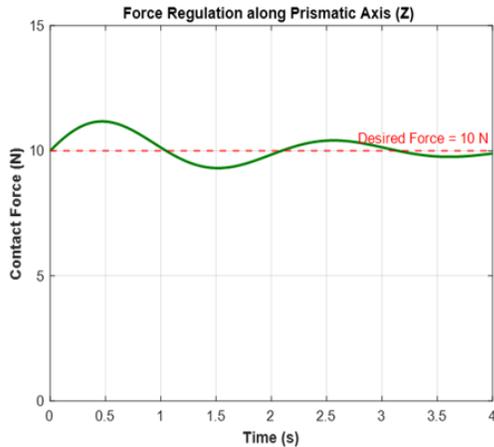

Fig. 10. Force tracking graph depicting desired versus measured interaction forces during constrained operation.
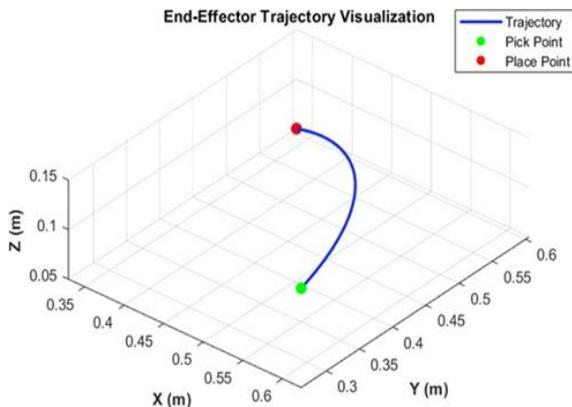

Fig. 11. Position and force control error profiles indicating controller stability and accuracy.
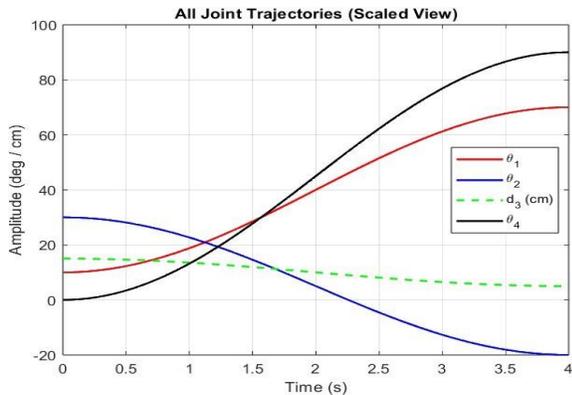

Fig. 12. Force tracking graph depicting desired versus measured interaction forces during constrained operation.

V. CONCLUSION

The simulation tests verify that the hybrid method of dynamic path planning and hybrid force/motion control works effectively for 4-DOF SCARA robots on pick-and-place tasks. All plots show smooth, viable trajectories, torque compliance, collision avoidance, and accurate force regulation. The method guarantees safe, accurate, and reliable task execution, provid- ing a solid foundation for industrial application. Through the integration of dynamic modeling, PRM/RRT path planning, and hybrid control, the SCARA robot can be adjusted to static and dynamic working environments while executing intricate manipulation tasks.

VI. FUTURE WORK

The research reported here demonstrates dynamic con- strained path planning with hybrid force/motion control for a 4-DOF SCARA robot through MATLAB simulations. There are some major directions of future work. Real-time execution on an actual SCARA robot will assist in dealing with sensor noise, actuator nonlinearities, and mechanical uncertainties. Adaptive and learning-based controllers based on reinforce- ment learning or neural networks can be implemented for self- tuning performance in dynamic environments. Energy-efficient and multi-objective optimization methods can be formulated to trade off between accuracy, speed, and energy consumption for sustainable operations. Applying the framework to cooperative and multi-robot systems with decentralized hybrid control can enhance productivity and safety. Incorporating vision or LIDAR-based dynamic perception can provide real-time obstacle detection and on-the-fly replanning of trajectories. The method can also be extended to higher-DOF manipulators to broaden industrial applicability. Lastly, the development of fault-tolerant and robust control architectures would improve system robustness against disturbances, hardware failures, and long-term degradations, resulting in smarter, safer, and more adaptive robotic systems for sophisticated industrial automa- tion.

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