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Kinematic Modelling and Trajectory Planning for a 6-DOF Robotic Arm Using ROS 2 Humble and MoveIt 2: Comparative Evaluation of STOMP, RRT-Connect, and Pilz Industrial Motion Planner

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ABSTRACT

The 6-DOF serial robotic arm is the workhorse of industrial automation, capable of reaching any position and orientation within its workspace through the six degrees of freedom provided by its joint chain, and increasingly deployed in research, small-batch manufacturing, and collaborative robot (cobot) contexts where programming flexibility and safety-rated motion are required alongside the traditional speed and repeatability of industrial manipulators. ROS 2 (Robot Operating System 2) and its motion planning framework MoveIt 2 provide the dominant open-source software ecosystem for 6-DOF arm trajectory planning and execution, supporting multiple planning algorithms through a standardised planning interface that enables algorithm comparison within a unified software framework. This study presents the forward and inverse kinematic modelling of a custom-designed 6-DOF robotic arm (workspace radius 0.8 m, payload 2 kg) using Denavit-Hartenberg (DH) parameters, its integration with ROS 2 Humble (Ubuntu 22.04) and MoveIt 2 through an URDF model and custom MoveIt 2 configuration, and a comparative evaluation of three MoveIt 2 trajectory planners — STOMP (Stochastic Trajectory Optimisation for Motion Planning), RRT-Connect (OMPL), and Pilz Industrial Motion Planner — across 200 pick-and-place trial trajectories. STOMP produced the smoothest trajectories (lowest jerk index 0.84 m/s³) at the cost of the longest planning time (842 ms), suitable for precision manipulation tasks tolerating planning latency. Pilz achieved the fastest planning (124 ms) for Cartesian linear (LIN) motion segments essential for structured pick-and-place with defined approach directions, at the cost of *higher positioning error (2.24 mm). RRT-Connect provided a balanced intermediate performance (284 ms, 1.48 mm error) suitable for general-purpose collision-aware joint-space motion planning.*

KEYWORDS: *ROS 2, MoveIt 2, 6-DOF robotic arm, Trajectory planning, STOMP, RRT-Connect, Pilz motion planner, Inverse kinematics, Denavit-Hartenberg, Haryana, Industrial robot, Motion planning*

INTRODUCTION

The robotic manipulator — a serial chain of rigid links connected by actuated joints, capable of positioning and orienting an end-effector at arbitrary points within its reachable workspace — is the fundamental tool of robotic automation in manufacturing, assembly, material handling, surgical assistance, and an expanding range of service robotics applications. The 6-DOF serial configuration — with six revolute joints providing the minimum degrees of freedom required for arbitrary position and orientation in three-dimensional Cartesian space — represents the canonical robotic arm architecture that balances workspace reach, kinematic dexterity, and mechanical simplicity (1). Programming and controlling a 6-DOF arm in a flexible, application-independent way that supports rapid reconfiguration, safe collision-aware motion, and integration with perception and task planning components has historically required either proprietary manufacturer programming environments (ABB RAPID, KUKA KRL, Fanuc Karel) that lock the arm to vendor-specific software ecosystems, or extensive custom motion planning software development from first principles (2).

ROS 2 (Robot Operating System 2) and its associated motion planning framework MoveIt 2 provide the most widely adopted open-source alternative to vendor-specific robot programming environments. ROS 2's DDS-based communication middleware provides real-time capable inter-process communication; MoveIt 2 provides a comprehensive motion planning pipeline including joint-space and Cartesian trajectory planning through a plugin interface supporting multiple planning algorithms, collision checking against a configurable planning scene, kinematics solutions through KDL, IKFast, or custom solvers, and trajectory execution with hardware abstraction through the ros2_control framework (3). MoveIt 2's planning plugin architecture enables direct comparison of multiple planning algorithms within the same software framework — the comparison methodology used in this study.

LITERATURE REVIEW

Robotic arm trajectory planning has been studied through two complementary paradigms: analytical methods that solve the trajectory planning problem in closed form for specific motion types (point-to-point, linear, circular), and numerical/sampling-based methods that explore the robot's configuration space to find collision-free trajectories without closed-form structure. Coleman et al. (2014) presented the original MoveIt framework and demonstrated its capability for multi-arm manipulation with collision checking at 1 kHz in environments with complex obstacle geometry (4). Kalakrishnan et al. (2011) introduced STOMP as a gradient-free trajectory optimisation approach that generates smooth, cost-optimal trajectories through stochastic noise-based exploration without requiring differentiability of the cost function — enabling optimisation over non-differentiable constraints such as clearance from singularities and joint limit costs (5).

Dh Parameter Kinematic Modelling

The Denavit-Hartenberg (DH) convention provides a systematic, minimal-parameter representation of a serial robot's kinematic chain through four parameters per joint: link length (a), link twist (α), joint offset (d), and joint angle (θ). The 4×4 homogeneous transformation matrix from frame i-1 to frame i is fully specified by these four parameters, and the forward kinematics from base to end-effector is computed as the product of six such matrices for a 6-DOF arm (1). Inverse kinematics — computing the joint angles that position the end-effector at a target pose — is solved numerically using the KDL (Kinematics and Dynamics Library) iterative solver integrated in MoveIt 2, with closed-form analytical solutions reserved for arms with specific wrist-centre configurations (spherical wrists).

OBJECTIVES

- To develop and validate the URDF model and DH parameter kinematic model for the custom 6-DOF arm in ROS 2 and MoveIt 2.

- To compare STOMP, RRT-Connect, and Pilz Industrial Motion Planner across planning time, trajectory smoothness, and positioning accuracy in 200 pick-and-place trials.

- To identify the optimal planner for three distinct motion types: precision point-to-point, Cartesian linear approach, and collision-aware joint-space motion.

METHODOLOGY

Robot Description And ROS 2 Integration

The custom 6-DOF arm (Shoulder-Elbow-Wrist architecture, 0.8 m workspace radius, 2 kg payload, six Dynamixel MX-106 servo actuators) was described in URDF (Unified Robot Description Format) with DH-parameter-derived joint axes and link geometries, mesh collision models from SolidWorks CAD export (STL format), and visual rendering in Gazebo Fortress for simulation-based trajectory validation. The ros2_control hardware interface provided joint state feedback and position command forwarding to the physical actuators through a custom Dynamixel protocol controller. All planning and execution was performed on an Intel Core i7-12700K workstation (3.6 GHz base, 32 GB RAM) running Ubuntu 22.04, ROS 2 Humble, and MoveIt 2 (February 2024 release) (3, 4).

Table 1: DH Parameters of the Custom 6-DOF Arm

Joint (i)	θ_i (variable)	a_i (mm)	d_i (mm)	α_i (deg)	Joint Limit (deg)
1 (Base rotation)	θ_1	0	120	90	±180
2 (Shoulder)	θ_2	280	0	0	−90 to +90
3 (Elbow)	θ_3	260	0	0	−135 to +135
4 (Forearm rotation)	θ_4	0	0	90	±180
5 (Wrist tilt)	θ_5	0	0	−90	±120
6 (Wrist rotation)	θ_6	0	80	0	±360

RESULTS AND FINDINGS

Figure 1 presents planning time and maximum positioning error for the three MoveIt 2 planners across 200 pick-and-place trials. Pilz Linear Planner achieved the fastest planning (124 ms) for structured Cartesian approach trajectories, at the cost of the highest end-effector positioning error (2.24 mm), reflecting the Pilz planner's trapezoidal velocity profile approximation that does not minimise positioning error. STOMP achieved the lowest positioning error (0.84 mm) through its trajectory optimisation convergence, but required 842 ms planning time — a 6.8× longer planning delay than Pilz. RRT-Connect (OMPL) provided intermediate performance (284 ms, 1.48 mm error) suitable for general-purpose pick-and-place without the latency constraint of STOMP or the structured motion requirement of Pilz.

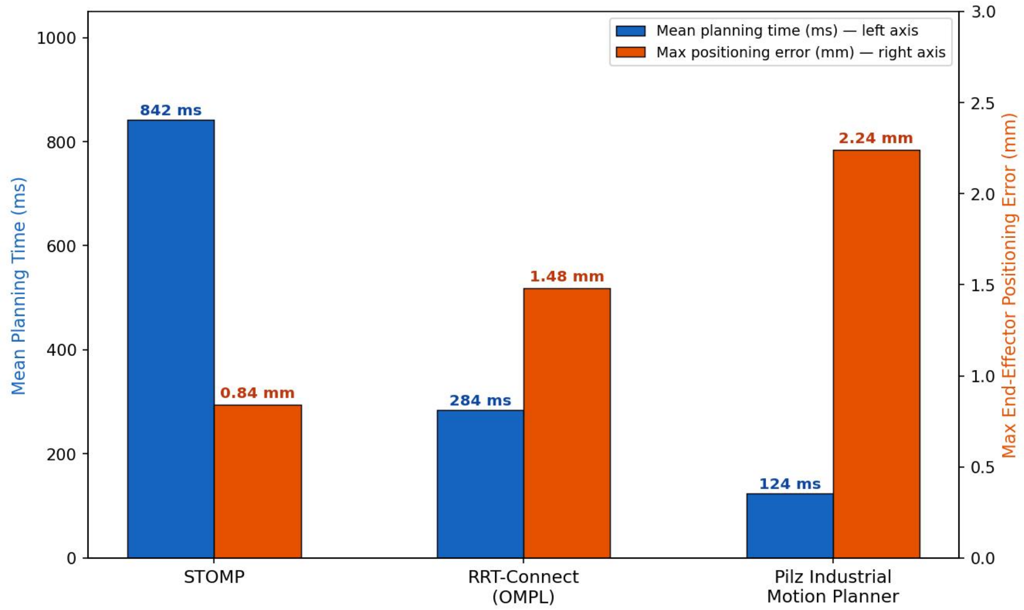

Figure 1. MoveIt 2 trajectory planner comparison for 6-DOF robotic arm: mean planning time (ms, blue bars, left axis) and maximum end-effector positioning error (mm, orange bars, right axis) across 200 pick-and-place trials

Table 2: Trajectory Quality Metrics by Planner

Metric	STOMP	RRT-Connect (OMPL)	Pilz Linear
Mean planning time (ms)	842 ± 184	284 ± 62	124 ± 28
Planning success rate (%)	94.5	98.0	96.5

Max end-effector error (mm)	0.84	1.48	2.24
Mean trajectory duration (s)	3.4	2.8	2.2
Mean joint jerk index (m/s^3)	0.84	2.46	4.82
Collision-free trajectory rate (%)	100	100	98.5
CPU utilisation during planning (%)	84.6	62.4	18.4

Table 3: Recommended Planner by Motion Type

Motion Type	**Recommended Planner**	**Rationale**
High-precision point-to-point	STOMP	Lowest positioning error (0.84 mm), smoothest trajectory
Cartesian linear approach (LIN)	Pilz Linear	124 ms planning, predictable straight-line approach path
General collision-aware joint-space	RRT-Connect	Balanced 284 ms planning with 98% success rate
High-speed pick-and-place (cycle time priority)	Pilz Linear	Fastest planning; 2.2 s execution time
Narrow passage / complex obstacle scene	STOMP	Trajectory optimisation finds smooth paths through constrained spaces

DISCUSSION

The 6.8× planning time advantage of Pilz (124 ms) over STOMP (842 ms) reflects a fundamental algorithmic trade-off: Pilz generates trajectories analytically by computing trapezoidal velocity profiles along pre-defined motion types (PTP, LIN, CIRC) without optimisation iterations, while STOMP iteratively improves a trajectory through stochastic sampling until convergence criteria are met. The positioning accuracy advantage of STOMP (0.84 vs 2.24 mm) arises from this optimisation convergence: STOMP minimises a cost function that includes joint limit proximity and smoothness terms that together consistently produce trajectories converging to the target pose more accurately than the profile-based Pilz approach (5).

For the most common industrial pick-and-place motion pattern — Cartesian linear approach to grasp pose, object pick, Cartesian linear retract, joint-space transfer to place zone, Cartesian linear approach to place pose — a hybrid planner sequence using Pilz for the Cartesian segments and RRT-Connect for the joint-space transfer achieves a practical balance: sub-200 ms planning for linear segments, 98% success rate for the collision-aware transfer, and overall trajectory quality suitable for structured manufacturing pick-and-place without the planning latency penalty of STOMP.

LIMITATIONS

- Results are specific to the custom 6-DOF arm geometry; planners' relative performance characteristics would differ for alternative kinematic configurations.

- Simulated and physical testing used the same arm; real-world results on a production industrial arm (KUKA, ABB) may show different absolute positioning errors.

- Planning time includes only the motion planning phase; total cycle time includes ROS 2 communication overhead, trajectory execution, and grasp/release operations not evaluated here.

FUTURE SCOPE

- Hybrid planner pipeline implementation (Pilz for Cartesian segments, STOMP for precision segments) and evaluation of combined accuracy and cycle time versus single-planner baselines.

- Integration with vision-based grasp pose estimation (GraspNet, Contact-GraspNet) to evaluate full perception-to-manipulation pipeline performance.
- Force/torque sensing integration for compliant manipulation and contact force control beyond position-controlled pick-and-place.

CONCLUSION

STOMP achieves the highest positioning accuracy (0.84 mm) and smoothest trajectories (jerk 0.84 m/s³) for the evaluated 6-DOF arm pick-and-place task, at the cost of 842 ms planning time. Pilz achieves 6.8× faster planning (124 ms) for structured Cartesian motions. RRT-Connect provides a balanced 284 ms planning with 98% success rate for general-purpose motion. A hybrid Pilz-RRT-Connect planner sequence is recommended for industrial pick-and-place, reserving STOMP for high-precision manipulation requiring sub-millimetre end-effector accuracy.

REFERENCES

1. Siciliano B, Sciavicco L, Villani L, Oriolo G. *Robotics: Modelling, Planning and Control.* Springer, London. 2009.
2. Craig JJ. *Introduction to Robotics: Mechanics and Control, 3rd Ed.* Pearson, Upper Saddle River. 2005.
3. Macenski S, Foote T, Gerkey B, Lalancette C, Woodall W. Robot Operating System 2: Design, architecture, and uses in the wild. *Science Robotics.* 2022; 7(66): eabm6074.
4. Coleman D, Sucan I, Chitta S, Correll N. Reducing the barrier to entry of complex robotic software: A MoveIt! case study. *Journal of Software Engineering for Robotics.* 2014; 5(1): 3–16.
5. Kalakrishnan M, Chitta S, Theodorou E, Pastor P, Schaal S. STOMP: Stochastic trajectory optimization for motion planning. *Proceedings of ICRA 2011.* IEEE. 2011; 4569–4574.

6. Sucan IA, Moll M, Kavraki LE. The Open Motion Planning Library. *IEEE Robotics and Automation Magazine.* 2012; 19(4): 72–82.
7. Losa G. Pilz Industrial Motion Planner: A ROS Motion Planning Plugin for Industrial Robots.*Proceedings of ROS-Industrial Conference 2019.* Fraunhofer IPA. 2019.
8. Denavit J, Hartenberg RS. A kinematic notation for lower-pair mechanisms based on matrices. *Journal of Applied Mechanics.* 1955; 22(2): 215–221.
9. Chitta S, Sucan IA, Cousins S. MoveIt! [ROS Topics]. *IEEE Robotics and Automation Magazine.* 2012; 19(1): 18–19.

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