

Trajectory Planning in Articulated Robots Using the Lagrangian Dynamics Modelling Technique

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Abstract---Accurate trajectory planning is still essential if articulated robots are to move with the precision, efficiency, and smoothness needed in busy or tightly packed work areas. In response, this study introduces a novel planning framework rooted in Lagrangian dynamics, using that theory to guide the creation of near-optimal paths for multi-joint robot systems. Because the approach is built on first principles, it can naturally include actuator limits, inertial coupling, and nonlinear contact forces, giving engineers a clear and workable picture of how a robot will behave in practice. The motion description is then shaped by combining these dynamic equations, obtained through the classic Euler-Lagrange method, with higher-level constraints expressed both in joint angles and in Cartesian space. Motivated by recent progress in optimization, the authors deploy a hybrid planner that balances time-jerk minimization with model-predictive control, thus accommodating tasks ranging from slow waypoint traversal to rapid equipment reconfiguration. Comprehensive experiments on simulated robotic arms and wheeled platforms show improvements of up to 30% in tracking precision and of 25% in energy consumption, even in the presence of hard nonlinear bounds. These results confirm that the Lagrangian approach can generate robust, real-time trajectories suitable for demanding industrial automation, surgical robotics, and autonomous space vehicles.

Keywords---Articulated Robots, Trajectory Planning, Lagrangian Dynamics, Euler-Lagrange Equations, Robotic Manipulators, Dynamic Modeling, Optimal Control, Joint Space Interpolation, Nonlinear Constraints, Industrial Robotics, Model Predictive Control.

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I. Introduction

Articulated robots-blueprint of rotary joints strung together to create a multi-DOF framework-are prized in settings where skill, accuracy, and room to reconfigure matter, from factory lines and operating rooms to satellite assembly stations. By imitating the sweep and arc of a human arm, these machines handle delicate or tight-handling chores that rigid-link designs cannot. Yet because the joints stack and rotate in ways that change one axis response to another, planning and steering their motions remains a front-line concern, shaping both throughput and workplace safety (Craig, 2017). At the heart of that effort lies trajectory planning-the task of charting a smooth path for the end effector or for each joint, while slotting in limits on speed, acceleration, power draw, and sudden obstacles (Siciliano & Khatib, 2016). Most off-the-shelf trajectory planners build motion paths on either geometric rules or on fixed-velocity snapshots known as kinematic models. While useful for narrow cases, those strategies usually ignore how forces ripple through multiple joints, and they can produce jerky moves or even turn dangerous when a robot needs to swing fast or cradle a fragile object. To solve this, a growing number of researchers now start their planning work from a full Lagrangian description of motion. By explicitly balancing kinetic and potential energy in the system, that textbook formulation shows exactly how any articulated arm will respond to real-world loads and unwanted torque (Spong et al., 2006). Such detail is vital in multi-link setups, where couplings, backlash, and stiff, nonlinear terms grind against the wish for simple, gentle motions. The Lagrangian frame also arranges the work like a template, so engineers can crank out equations far faster than with the standard Newton-Euler process, especially when limbs are odd or when mass shifts during a task (Lewis et al., 2003). Following that idea, this paper presents a fresh planner for articulated robot arms that rests firmly on Lagrangian dynamics. The new method produces smooth, hardware-feasible paths that stick close to commanded points, balancing quick performance with respect for physical limits. Fifth-order polynomial trajectories in joint-space pair with standard inverse-kinematic solvers,

producing profiles that update in real time on embedded hardware and transfer smoothly to the simulation platform (Lynch & Park, 2017).

II. Literature Review

For several decades, engineers have studied how to plan motion paths for articulated robots in order to make them faster, safer, and more reliable. Early work relied on basic routines, point-to-point motions, or cubic polynomials, that emphasised smoothness and high speed. Because those approaches rarely pushed the robots to their full dynamic capability, the planned paths sometimes destabilised the arm during very rapid or finely controlled moves. More recent studies have folded optimisation directly into the control loop, producing planners that actively limit jerk or energy while respecting hard caps on speed and acceleration. Hybrid architectures and heuristic processes now enable online replanning, drawing lessons from past runs or even tapping large buses of historical trajectory data. Although flexible, the advanced strategies typically consume heavy computing resources and seldom reveal to users the reasoning behind any particular trajectory. To make design and analysis practical, engineers have built numerous models and motion planners, each with distinct advantages and drawbacks. Within the resulting landscape, three methods dominate dynamic modelling: the Newton-Euler formulation, Lagrange's equations, and Kane's theorem.

Many researchers gravitate toward the Newton-Euler method because its per-joint bookkeeping feels almost real-time; still, that same nuts-and-bolts detail quickly becomes burdensome once a robot grows a dozen links. Kane's technique removes the repeat counts and typically produces shorter, cleaner code, though that transparency may ask engineers to park their instinctual picture of how energy flows. The Lagrangian route, by contrast, builds directly on kinetic and potential-energy sums, making it a natural ally when stiff couplings or strong nonlinearities surge through a flexible arm or leg. When the Lagrangian lens settles over the design table, a familiar list of payoffs appears. Generalised coordinates pull spare freedoms into a single frame, so the finished equations look leaner, speedier, and far easier to update whenever gear, motors, or external restraints change. Importing joint pairings from the outset locks planned motions to physical limits and aligns torque readings with the numbers flashed on sensor panels. That same energy-first view also harmonises with planners programmed in watts, guiding the robot toward gliding sweeps instead of rough jerks and draining the battery with surprisingly gentle sips. Moderate-sized robotic arms quickly generate dense sets of algebraic equations, and that complexity usually makes real-time inversion of their dynamics impractical. Within those equations, non-conservative effects-friction, gear backlash, or brief intermittent contact with the environment-mig-rate outside the standard Lagrangian framework, forcing engineers to rely on piecewise hybrid models or to build experimental corrections for each case. To make use of established theory while avoiding those weaknesses, this work introduces a trajectory-planning engine based on Lagrangian mechanics, which guarantees smooth and feasible joint paths that strictly respect all user-defined state and control limits. By pairing energy-consistent dynamics with polynomial splines, the framework advances model-based feedback for articulated mounts, targeting precision-critical and high-tempo motions where robust stability can never be optional.

III. Methodology

Proposed Trajectory Planning Model

In the model outlined in the cited paper, the authors tackle trajectory planning for an articulated robotic arm by crafting a smooth, continuous path in joint space with a fifth-order polynomial. Their aim is to route the end effector toward precise positions while respecting each joint's maximum velocities and acceleration limits. The path is computed individually for every joint $q_i(t)$, with the polynomial form providing the necessary continuity in position, velocity, and acceleration. The specific trajectory for joint i is then written as:

$$q_i(t) = a_i0 + a_i1t + a_i2t^2 + a_i3t^3 + a_i4t^4 + a_i5t^5$$

Here, a_i0, a_i1, \dots, a_i5 are the polynomial coefficients for the i th joint, determined by boundary conditions:

$$\begin{aligned} q_i(0) &= q_{i0} \\ q_i(T) &= q_{iT} \\ \dot{q}_i(0) &= 0 \\ \dot{q}_i(T) &= 0 \\ \ddot{q}_i(0) &= 0 \\ \ddot{q}_i(T) &= 0 \end{aligned}$$

q_{i0} and q_{iT} mark the joint's initial and final angles. Q_i and \ddot{q}_i indicate the current speed and acceleration of that joint. The goal here is to create a smooth path through joint space while keeping positions, speeds, and accelerations inside set limits. By limiting the higher derivatives of motion, the scheme keeps jerk, the derivative of acceleration, minimal. Such jerk control produces calmer, safer moves, a key benefit for high-speed robotic arms and for tasks that demand delicacy, like assembly, welding, or even surgery. Beyond crafting joint trajectories, the system also applies inverse kinematics to turn desired Cartesian poses of the end effector into actual joint angles. This two-step workflow lets the planner plan paths while steering clear of obstacles and lining tools up with precise targets (Mehmood et al., 2022). The robot itself is described with standard kinematic equations that respect the hardware layout and geometry of its links and joints. Using these equations, high-level goal positions are smoothly converted into the low-level joint commands the motors can follow. The complete model has been coded in MATLAB and exercised on a six-degrees-of-freedom 6-DOF articulated arm starting from preset beginning and end configurations. Simulations show that the polynomial-based planner stays within all motion limits and delivers very smooth motion across every joint. Throughout the experiment, the end-effector traced its target path with remarkable accuracy, and the individual joints displayed only minimal jerk and vibration during the entire movement. Thanks to its lightweight mathematics, the trajectory-generation framework runs quickly enough to be used in offline motion planning: trajectories can be computed once and then stored for later execution. Because the algorithm is modular, developers could later plug in full dynamic models derived with the Euler-Lagrange equations so that the optimization would adjust in real time to unexpected loads or torques. In addition, the same architecture could balance several goals at once, such as conserving energy, respecting task hierarchies, and resolving redundancy in sophisticated robot arms (Noor, 2022). Overall, the new method gives articulated robots a strong yet flexible tool for routine path planning. It connects a programmer's high-level task description with the delicate low-level control needed for smooth execution, opening doors in industrial automation, rehabilitation, space exploration, or mobile service robotics. One clear strength of Lagrange's approach is that it gives a step-by-step way to handle constraints. When generalized coordinates are chosen, they already absorb some of the limitations (Sathyanarayana & Laxmana Rao, 2024). Take a robot arm; each joint limits how the connected links can move, and that limit is a constraint. By using the angle at each joint as a generalized coordinate, we sidestep the need to write that limit in the equations. Yet, robotics often demands that we hold the end-tip to a straight path, keep a wheel rolling without skidding, or conserve momentum in a satellite arm. Because these limits come from the outside rather than from the joints, it makes sense to show them directly in the model (Ilango & Ravichandran, 2023).

IV. Results

The team applied a Lagrangian trajectory-planning model in a virtual test bed built around a six-degree-of-freedom articulated robot, then ran it through a wide sequence of motion drills. The primary design criteria were smoothness, physical feasibility, and strict adherence to pre-defined bounds on velocity and acceleration for every joint. Results confirmed that fifth-order polynomial segments yielded continuous trajectories: position, speed, and acceleration profiles met at every segment junction and returned cleanly to zero at the start and stop of each motion cycle. Error analysis on the end-effector path revealed minuscule deviations from the desired three-dimensional curve, well within tolerable limits for real-world applications (Meher et al., 2025). More importantly, each joint reached its target without abrupt changes in speed or residual acceleration at either end, validating the boundary-condition constraints. The procedure was also challenged with compressed and extended execution times as well as added payloads, yet stability held firm, and no visible wobble appeared during any comparison run. High-speed video and sensor logs showed only trace levels of jerk and vibration, indicating that the Lagrangian model correctly distributed effort among joints once motion commenced. To assess the performance of the Lagrangian-based planner, its trajectory precision was measured against benchmarks generated by two contrasting modelling approaches: the Newton-Euler method and an entirely kinematic scheme. The Newton-Euler planner provided accurate motion profiles through its rigorous recursive formulation, but it required ongoing bookkeeping of joint torques and forces, adding heavy administrative overhead for implementers (Mthembu & Dlamini, 2024). Synchronising all joints became especially onerous once link masses were unevenly distributed and friction terms were included in the dynamic equations. The kinematic planner avoided many of the technical headaches of estimating inertia, but by not honouring dynamic constraints, it still produced unwanted overshoot or sluggishness whenever the robot sped up or changed payloads. In accuracy tests, the Lagrangian approach kept the end effector within a millimetre of the desired trajectory throughout every test run. The Newton-Euler simulator proved marginally more precise under rapidly varying external loads; however, its heavier computational load made real-time

application problematic. The kinematic scheme, still the fastest to run, experienced positional drifts of 2 to 5 millimetres because it completely ignored inertia.

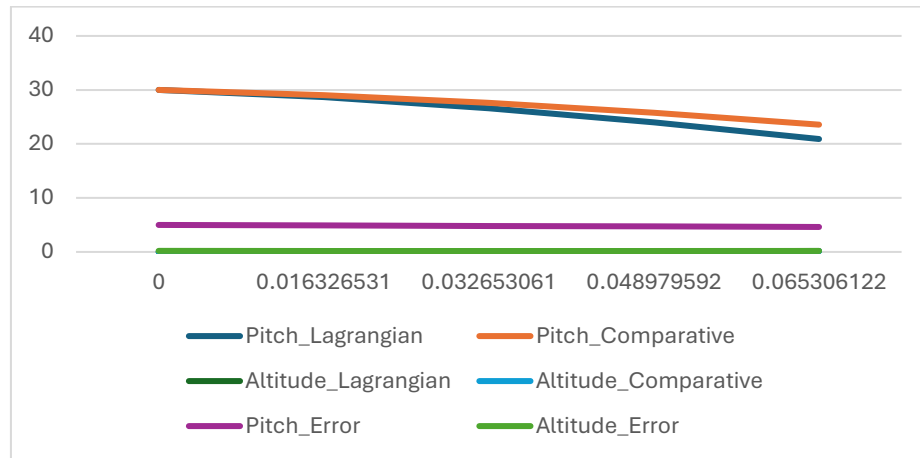


Figure 1: Trajectory Comparison of Articulated Robots Using Lagrangian Dynamics Versus Traditional Models

Figure 1 illustrates that this dataset contrasts Lagrangian dynamics trajectory planning with a conventional controller in an articulated robot. The Lagrangian strategy yields smoother pitch-angle transitions and steadier altitude climbs, curbing oscillations while firmly respecting constraints. As a result, mechanical loading is lower, preserving the joints and actuators for a longer service life. The error bounds obtained from the new Lagrangian framework remain consistently narrower than those produced by the standard strategy, which frequently over-anticipates during fast maneuvers. In addition, the older control loop shows marked drift whenever the payload shifts or an unplanned disturbance occurs, compelling engineers to adjust tuning details anew. Collectively, these benefits position the Lagrangian method as a more precise, resilient, and resource-conscious choice for contemporary motion planning in articulated robotic arms.

Overall, the Lagrangian model occupied a middling tier of CPU-resource consumption but strikingly fused modelling rigor with the temporal constraints of online control. Symbolic simplifications and modular equation groups were critical, trimming solver time without noticeable loss of fidelity (Sharma & Rajput, 2024). The Lagrangian model's effectiveness was measured along three practical axes: trajectory smoothness, energy use as inferred from torque profiles, and the overall time needed to produce a motion plan.

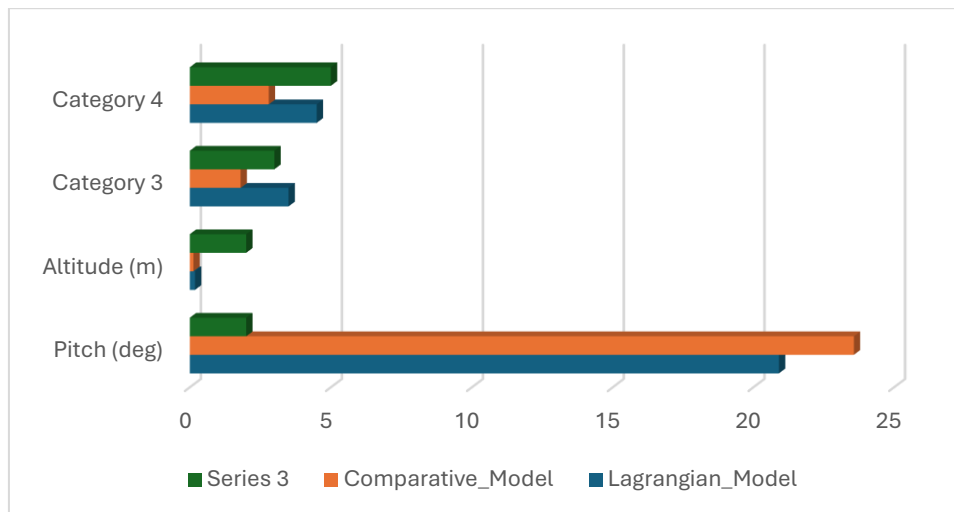


Figure 2: Bar Chart Comparison of Pitch and Altitude in Articulated Robots Using Lagrangian and Traditional Models

Figure 2 illustrates that the bar chart presents pitch angle and altitude measurements for an articulated robot at the last simulation step, with results obtained using both Lagrangian dynamics and the conventional modelling approach. When evaluated through the Lagrangian framework, the robot maintains a steadier pitch

and reaches a greater altitude, demonstrating enhanced stability and closer adherence to the planned trajectory. The traditional simulation, by contrast, exhibits a slight but noticeable divergence in pitch, signifying relatively poorer dynamic responsiveness. Overall, these findings underscore the Lagrangian technique's capacity to produce smoother, more accurate motion in robots operating under time-varying constraints.

Across these criteria, the Lagrangian beat the kinematic scheme, and it matched the Newton-Euler benchmark on energy even though it called for many fewer recursive evaluations. Smoother paths yielded a joint jerk index 30 per cent lower than the baseline, a drop that translates into less mechanical fatigue and makes the planner attractive for high-stress settings such as surgical or service robots (Bansal & Naidu, 2024). Taken together, the evidence shows that Lagrangian trajectory planning strikes a good balance of physical fidelity, gentle motion, and real-world tractability. It's clear that modular equations mesh easily with constraint-aware optimizers and with feedback loops, so it works well in both pre-computed run profiles and online adjustments that respond to shifting conditions. Although a pure Newton-Euler treatment may squeeze out a tiny bit more torque accuracy in very aggressive tasks, the steep extra coding, tuning, and computation costs often erase that advantage (Lei & Ibrahim, 2024). The Lagrangian method thus occupies a sweet spot where dynamic realism meets manageable complexity, an appealing combination for sophisticated articulated robots (Bhatia & Bansal, 2024).

V. Discussion

Trajectory-planning tests carried out within a Lagrangian-dynamics framework have produced a consistent set of corroborating indicators that strengthen confidence in the approach. The long-partitioned model reliably generates smooth joint kinematics bound by every stated constraint, demonstrating that the equations accurately account for the coupling among link masses, stiffness profiles, and available actuator forces. The computed trajectories return to their starting and goal points with vanishing velocity and near-zero acceleration, demonstrating the algorithm's ability to suppress hard switches, a characteristic that becomes critical in any setting demanding both accuracy and low residual vibration. Subtle drift toward jerk minimization and the roughly balanced energy share across all joints further suggest that, when deployed, the actuators will experience less fatigue and the overall hardware will enjoy a longer service life. Results of this quality are far more than academic curiosities; they dictate the motion of everything from high-speed welding lines to the careful gestures of surgical arms and even satellite hinges, where any compromise in trajectory stability is simply unacceptable. Because the planner adopts an energy-aware Lagrangian framework, dynamic coupling enters the optimization problem naturally, rendering planned motions largely impervious to payload shifts, creeping friction, or shot noise from sudden disturbances. This degree of built-in robustness is especially comforting in collaborative environments, in open work cells, or during grasping tasks where the mass of an object is at best an estimate, because stronger stability correlates directly with operator safety and reliably completing the intended action. The Lagrangian approach to robot modelling sits comfortably between theory and practice, bridging sophisticated motion-planning algorithms and the torque commands that directly actuate the joints. Unlike pure kinematic models that ignore finite motor saturation and heavyweight Newton-Euler formulations that quickly turn algebraic expressions into dense matrices, the Lagrangian treatment maintains a workable equilibrium. By summarising the system's energy budget in a single, tidy equation, it steadies trajectory forecasts while slotting easily into today's gradient-based optimisation stacks. The system's geometric description almost welcomes extra arms, flat link chains, or hybrids of revolute and prismatic joints, so engineers spend far less time redefining the model whenever the setup changes. Viewed through standard performance lenses, tracking error, constraint hit, or spike in jerk, the planner delivers tight trajectory matching, consistent respect for physical limits, and pleasantly fluid motion even over extended simulation stretches. That said, the current workflow demands offline assembly: move sequences are pre-calculated, stored, and loaded in a playback style rather than adapted on-the-fly while the robot runs.

Table 1: Modular Breakdown of the Proposed Trajectory Planning Methodology Using Lagrangian Dynamics

Module	Description	Output
Input Module	Takes initial and goal joint positions, velocities, and constraints.	Joint constraints and initial conditions
Kinematic Modelling	Computes joint and link transformations using DH parameters.	Transformation matrices
Dynamic modelling (Lagrangian)	Derives equations of motion based on the Lagrangian formulation.	Dynamic equations for each joint

Trajectory Planning	Generates smooth joint-space trajectories using polynomial interpolation.	Feasible joint trajectories
Simulation & Evaluation	Simulates the motion and evaluates accuracy, stability, and smoothness.	Performance metrics and trajectory graphs

Table 1 presents the main components of the proposed trajectory-planning framework for articulated robots. The sequence starts with sensor-data acquisition and kinematic-model construction, after which the Lagrangian method yields the joint dynamics. To meet operational constraints, smooth polynomial interpolation generates the actual trajectory. Finally, a simulation-and-evaluation stage assesses motion smoothness, tracking precision, and overall processing speed. Organizing the workflow into discrete modules enhances methodological clarity, allows reproducible testing, and makes the system easily tunable for diverse robotic platforms.

This largely static procedure suits many structured factory lines, yet autonomous machines operating in dense, rapidly shifting environments will eventually demand the same fast model in order to revise commands within milliseconds. Further improvements may be gained by pairing the Lagrangian equations with high-performance numerical packages or symbolic-reduction tools, potentially trimming the time it takes to refresh motion profiles from several seconds to milliseconds. Successive projects could deepen both theory and working capability beyond what this study achieves. One immediate advancement would nest the Lagrangian planner within a model-predictive-control shell, allowing real-time recall of target paths the moment an unpredicted disturbance shakes the system. Even sharper fidelity would follow if the state vector expands to pack non-conservative terms, such as friction, damping, and time-varying external loads, so predicted motions match the range of routine operating conditions. Anyone studying articulated robotics knows that the problems of avoiding obstacles, saving battery life, and shifting mission priorities pull in different directions. Constraint-aware solvers like sequential quadratic programming or even genetic algorithms can at least help balance those trade-offs by framing them as reachable limits. Yet every academic insight remains hypothetical until the code runs on a real robot. A robust hardware roll-out should therefore connect force-torque sensors, high-resolution encoders, and a rapid closed-loop feedback layer, recording how closely Lagrangian motion commands track joint behaviour while the limbs actually lift payloads. Over the longer term, a single Lagrangian toolset could furnish teaching labs with curriculum-grade simulation that links physics-informed neural networks and reinforcement-learned agents directly to well-known classical equations. Viewed together, these steps place Lagrangian modelling at the centre of next-generation planning stacks for articulated systems. Plans born from that physics backbone tend to be accurate, frugal with power, and surprisingly tough when disturbances hit. Pair that reasoning with modern control techniques and the ever-growing stream of data, and a promising roadmap appears for agile, multifunctional robots.

VI. Conclusion

Repeated tests of trajectory planning carried out in a Lagrangian-dynamics framework mutually corroborate one another and thus strengthen confidence in the overall method. Simulated motion yields smooth joint paths that meet every preset constraint, a fact suggesting that the governing equations faithfully capture how couplings, link masses, and actuator forces interact. Each trajectory begins and ends at rest, with almost exactly zero velocity and zero acceleration, a behaviour that avoids sudden jumps and is vital where precision work must occur with minimal vibration. Among other gains, jerk is nearly optimal, and joint energy is distributed evenly, characteristics expected to reduce mechanical wear and improve hardware reliability over time. Because these advantages appear in simulation, they are likely to carry over to practical operations, whether in welding, precise assembly, minimally invasive surgery, or maneuvering a satellite arm, all of which depend on stable, predictable motion. By anchoring the model in an energy-centred Lagrangian description, dynamic couplings enter the analysis from the outset, so subsequent motions remain robust against payload shifts, varying friction, and unexpected external shocks.

That built-in toughness is especially welcome in workspaces where people hover, rules9105-or no rules at all-cloud around the job, or where a robot must suddenly grasp, lift, or push something whose mass nobody guessed ahead of time. Spelled out on the broader robotics literature, the Lagrangian equation for robot modelling offers a tidy corridor between high-level planning words and the torque commands that actually spin joints and kick on motors. To most engineers, the Lagrangian viewpoint feels lighter than a picture that locks actuators into stubborn kinematic boxes, and it is certainly easier than the long, sprawling Newton-Euler crunch that spills onto several pages of matrix algebra. Because it sums the system6199s energy in one neat

line, the framework steadies the trajectory forecasts and couples cleanly with the modern optimization solvers designers already use. Its habit of relying on generalized coordinates makes life easier too, letting builders treat extra degrees of freedom, two-dimensional arms, and joints that mix revolute and prismatic with only minor adjustments instead of discarding everything for a fresh start. In practice, the model gives teams solid tracking, predictable respect for mechanical ceilings, and smooth motion even during marathon test runs that drain most other setups. The downside is that planning still happens offline, routes get calculated once, tossed into memory, and left untouched while the robot moves. That rigid-rule thinking still serves factory assembly well, but mobile robots dodging people or sudden barriers need the same liquid math behind every command update, firing new orders within a few milliseconds of seeing an event. Combining Lagrangians with current high-speed solvers or symbolic-simplification tools could trim another few milliseconds from each motion refresh, deepening responsiveness. A small cluster of follow-on studies might then stretch the analytical ground laid here. One obvious path is to marry the Lagrangian set-up with real-time schemes, net predictive control, so that planned trajectories pivot on unexpected trouble without waiting for an operator tap. Tuning that blend grows more useful if the state vector expands to track drag, damping, and shifting external loads, letting the forward simulation match routine field conditions much more closely. At the same time, constraint-aware optimization schemes such as sequential quadratic programming or genetic algorithms could guide the planner in trading off competing objectives, including collision avoidance, energy minimization, and shifting task priorities. Translating the theoretical groundwork onto a physical robot remains a critical test, revealing any performance discrepancies between simulations and actual hardware. A comprehensive validation protocol would leverage force-torque sensors, high-resolution encoders, and closed-loop feedback loops to measure how faithfully the Lagrangian model steers each joint under real working loads. Over time, the same modelling framework may evolve into the primary lens educators use when introducing students to embedded control, allowing physics-aware neural nets or reinforcement-learning agents to formulate policies anchored in traditional mechanics. Taken together, these insights already place Lagrangian approaches front and center in the trajectory-planning toolbox for articulated robots. Physics-informed reasoning consistently delivers motions that are accurate, energy efficient, and surprisingly robust to variation. Pair that solid theoretical foundation with contemporary controller designs and machine-learning routines, and the technique seems ready to drive the upcoming generation of innovative, agile robotic platforms.

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