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(REVIEW ARTICLE)

A Simscape Multibody-Based Approach for Enhanced Dynamic Simulation of 6-Axis Robots

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Abstract

In the field of robotic system simulation, traditional approaches often rely on mathematical models derived from the robot's kinematics and dynamics. However, these models face significant challenges when incorporating nonlinear effects such as joint friction, actuator behavior, and other. As a result, the simulation outputs tend to be idealized, reliability and limiting their use in practice. This paper proposes a for a 6-degree-of-freedom (6-DOF) robotic manipulator using MATLAB's Simscape Multibody environment. Unlike conventional methods, this approach allows for the direct integration of physical properties, constraints, and geometries based on 3D CAD models. The robot is represented as a multibody system connected through physical joints and domains, to real mechanical behavior. The proposed method is validated through comparative simulations, demonstrating its effectiveness and accuracy in replicating ideal motion scenarios. The study highlights the advantages of using for realism, design verification, and dependency on physical prototypes.

Keywords: 6-DOF Manipulators; Simscape Multibody; Six degrees-of-freedom

1. Introduction

Accurate modeling and simulation of robotic manipulators are foundational to modern robotics research and development, playing an essential role in the analysis, design, and validation of control strategies prior to physical deployment. Traditional modeling techniques—typically grounded in Newton–Euler or Lagrangian dynamics—have provided a robust mathematical foundation for representing robotic systems. However, these methods often struggle to accommodate the full range of nonlinearities encountered in real-world environments, including joint friction, actuator delay, structural compliance, and thermal or electrical dynamics [1], [2], [3].

To address these limitations, the field has increasingly embraced quasi-physical modeling, in which systems are represented through physically-based component interactions rather than abstract equations alone. A leading platform paradigm is Simscape Multibody, a MATLAB/Simulink-based toolset that enables engineers to model and simulate multibody mechanical systems using actual geometric and physical data from CAD sources [4], [5], [6].

The integration of CAD models directly into Simscape Multibody allows for automated extraction of critical physical parameters, such as mass properties and inertia tensors [7], [8], [9]. This approach offers unique advantages in robotic applications, where the interplay between kinematics, dynamics, and environmental effects is often too complex to model analytically. Studies have demonstrated the effectiveness of Simscape-based modeling in domains ranging from

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wind turbine gearboxes [10] and power electronics [11], to mobile manipulators [12], collaborative robots [13], and digital twins of industrial systems [14], [15].

Particularly for six degrees-of-freedom (6-DOF) robotic arms, for simulating complex behaviors under varying load conditions, trajectory profiles, and friction models. For example, Ngoc and Nguyen [1] developed a Simscape-based model of the ABB IRB 120, validating its performance through comparison with traditional mathematical models. Similarly, Zhang et al. [14], [15] highlighted the potential of Simscape for developing real-time digital twins of robot arms that reflect dynamic physical states, including joint frictions and inertial effects.

Beyond hardware realism, the platform supports seamless integration of physical phenomena such as Stribeck friction, Coulomb damping, and actuator latency, as well as control algorithms and sensor models [16], [17], [18]. These capabilities are essential for emerging applications involving fault detection [19], trajectory optimization [20], human-robot interaction [21], and machine learning integration [22].

The construction and validation of a quasi-physical model of a 6-DOF industrial robotic manipulator using Simscape Multibody. The model is developed from detailed CAD data, including link geometries, mass distributions, and joint constraints. The simulation results are compared with those from a conventional mathematical model, under identical torque and trajectory inputs. Our results highlight the improved fidelity, flexibility, and realism of quasi-physical models, application in early-stage design, control development, and virtual prototyping of robotic systems.

2. Background and Related Work

The modeling and simulation of robotic systems have evolved significantly in the last two decades. Classical approaches rely on Newton–Euler or Lagrangian mechanics to formulate the equations of motion of multibody systems [1], [2]. These models offer compact and mathematically sound representations, but they often lack the ability to capture complex, nonlinear phenomena such as friction, actuator dynamics, flexibility of links, and sensor latency [3]. To bridge this gap between idealized models and real-world behavior, researchers have increasingly adopted approaches. These methods treat the robot as a network of physically connected components and enable the simulation of mechanical interactions, joint forces, and real geometry. One of the most prominent tools approach is Simscape Multibody, a MATLAB/Simulink toolbox that allows for dynamic simulation of multibody mechanical systems based on physical principles [4], [5], [6].

Numerous studies have demonstrated the effectiveness of Simscape-based modeling. For instance, the quasi-physical model of the ABB IRB 120 robot developed by Ngoc and Nguyen [1] closely mimics the dynamic response of the real robot, even under non-ideal conditions such as joint friction. Similarly, Zhang et al. [7], [14] validated their Simscape-based digital twins of industrial robots using both simulation and experimental platforms. Its versatility across disciplines highlights its robustness and extensibility, especially when integrating sensor and actuator dynamics into the simulation environment [13], [15]. Joint friction, a nonlinear and often neglected factor in analytical models, can be efficiently modeled in Simscape through physical blocks. Several researchers have incorporated Stribeck, Coulomb, and viscous friction models using parameterized components [16], [17]. These can be tuned based on experimental data or manufacturer specifications, enabling high-fidelity simulations under realistic conditions.

The platform also facilitates multi-domain simulation, where joint dynamics, electrical drives, and feedback sensors are co-simulated. This has been employed in applications such as fault detection [19], trajectory planning [20], and human-robot interaction (HRI) [21]. The inclusion of machine learning-based components for adaptive control and system diagnostics has also been explored in recent works [22]. Moreover, advanced uses of Simscape include optimization of control trajectories and benchmarking simulation frameworks. Rossi and Bianchi [23] demonstrated how Simscape-based environments could be used for trajectory planning and motion optimization in closed-loop systems. Meanwhile, Wilson and Clark [24] conducted a comparative study of different simulation platforms, confirming that Simscape offers a solid balance between usability, precision, and integration with control logic.

In conclusion, the literature strongly supports the use of Simscape Multibody as a robust environment for building quasi-physical models of robotic systems. These models enable the inclusion of complex, real-world dynamics and provide a platform for simulation-driven design, testing, and validation of robotic arms. Building upon these foundations, a 6-DOF manipulator modeled in Simscape, with a focus on evaluating its dynamic performance under both frictionless and friction-included conditions.

3. Robot Modeling Methodology

The ABB IRB 120 is a 6-degree-of-freedom (6-DOF) industrial robotic manipulator designed for high-precision tasks. To develop an accurate kinematic and dynamic model of the IRB 120, we employ the standard Denavit–Hartenberg (D-H) convention to systematically define the spatial relationships between adjacent links. This methodology facilitates the derivation of the robot's forward and inverse kinematics and serves as the foundation for subsequent dynamic modeling and control. Its structure consists of 6 revolute joints allowing full spatial manipulation, making it ideal for high-precision operations in confined spaces.

The Denavit–Hartenberg (D-H) convention is used to define the transformation between adjacent links. The assignment of coordinate frames follows these rules:

- The z-axis aligns with the axis of rotation.
- The x-axis is perpendicular to the common normal.
- The origin is located at the intersection of the z-axis and the x-axis.

Table 1 D-H parameters of robot IRB 120

Link (i)	θ_i (variable)	d_i (mm)	a_i (mm)	α_i (rad)
1	θ_1	290	0	π/2
2	θ_2	0	270	0
3	θ_3	0	70	π/2
4	θ_4	302	0	-π/2
5	θ_5	0	0	π/2
6	θ_6	72	0	0

3.1. Forward Kinematics

The transformation from the base to the end-effector is expressed by:

$$T_6^0 = T_1^0 \cdot T_2^1 \cdot T_3^2 \cdot T_4^3 \cdot T_5^4 \cdot T_6^5 \quad \text{………. (1)}$$

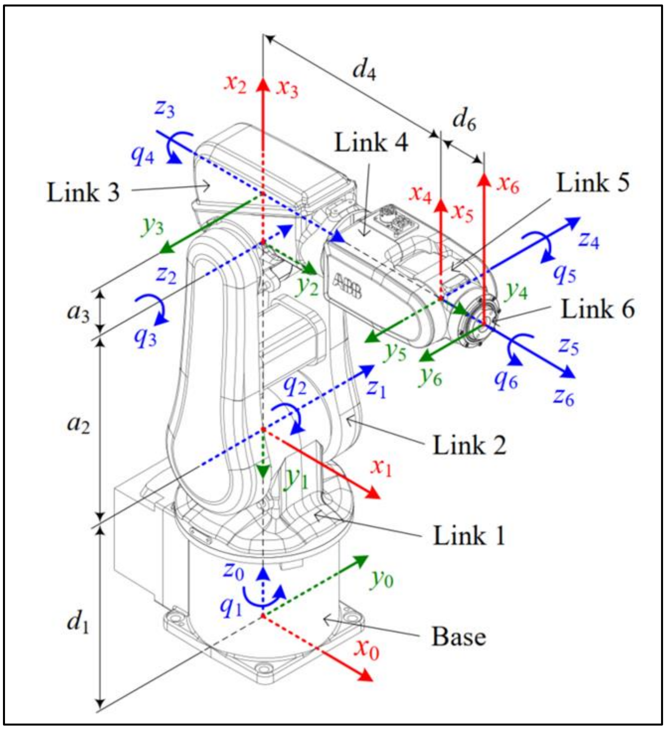

Figure 1 The attached coordinate frames for each link of the ABB IRB 120 robot based on the Denavit–Hartenberg convention

Where each transformation matrix T_{i+1}^{i} is derived from:

$$T_{i+1}^{i} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{.........} \quad (2)$$

3.2. Inverse Kinematics

The inverse kinematics for IRB 120 is obtained by solving geometric constraints to recover joint variables. The typical approach includes:

- Analytical separation of wrist and arm kinematics
- Solving for wrist center position and orientation
- Using trigonometric relationships to obtain joint angles

3.3. Dynamic Modeling

Using the Euler–Lagrange formulation, the dynamics of the robot are modeled by:

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) \quad \text{.............} \quad (3)$$

Where:
$q = [\theta_1, \theta_2, \ldots, \theta_6]^T$ is the joint angle vector.
M(q) is the inertia matrix.
$C(q, \dot{q})$ is the Coriolis and centrifugal matrix.
G(q) is the gravitational torque vector.

3.4. Inertia Matrix M(q)

$$M_{ij}(q) = \sum_{k=1}^{6} m_k \left(\frac{\partial x_k}{\partial q_i} \right)^T \left(\frac{\partial x_k}{\partial q_j} \right) + \sum_{k=1}^{6} J_{\omega_k, i}^T I_k J_{\omega_k, j} \quad \text{……….} \quad (4)$$

Where:
m_k is the mass of the k-th link
I_k is the inertia tensor
$J\omega_k$ is the angular Jacobian
Coriolis and Centrifugal Matrix $C(q, \dot{q})$

The Coriolis and centrifugal effects are captured using symbols:

$$C_{ijk} = \frac{1}{2} \left(\frac{\partial M_{ij}}{\partial q_k} + \frac{\partial M_{ik}}{\partial q_j} - \frac{\partial M_{jk}}{\partial q_i} \right) \quad \text{……..} \quad (5)$$

$$C_{ij} = \sum_{k=1}^{n} C_{ijk} \dot{q}_k \quad \text{…………} \quad (6)$$

3.5. Gravity Vector G(q)

The gravitational force vector is given by:

$$G(q) = \sum_{i=1}^{n} J_{v_i}^T m_i \mathbf{g} \quad \text{……………} \quad (7)$$

where is $\mathbf{g} = [0, 0, -9.81]^T$ the gravitational acceleration vector.

The comprehensive mathematical model of the IRB 120 robot, including kinematic parameters and dynamic equations, serves as the cornerstone for developing model-based control algorithms. With accurate representations of M(q), C(q, q̇), G(q), the system is suitable for simulation in MATLAB/Simulink and for implementing advanced control techniques in real-time applications.

4. Dynamic System Modeling of 6-DOF Robotic Manipulator in MATLAB Simscape Environment

The modeling and simulation of robotic manipulators play a crucial role in research, development, and deployment in both academic and industrial contexts. In recent years, the shift from purely symbolic mathematical models to using tools like MATLAB Simscape Multibody has significantly improved the accuracy and reliability of robot simulations. This method captures not only the kinematic and dynamic structure of robots but also incorporates non-linearities and physical behaviors such as joint friction and actuator dynamics.

The ABB IRB 120 is a lightweight, it features six revolute joints configured in a serial kinematic chain, allowing for high flexibility in movement. Traditionally, robotic dynamics are modeled using the Denavit-Hartenberg (DH) convention and derived through the Euler-Lagrange or Newton-Euler methods. While mathematically rigorous, these approaches have significant limitations when it comes to simulating physical non-linear effects such as friction, actuator lag, or gear backlash, which are often simplified or ignored. As a result, simulations based on mathematical models may be idealized and fail to reflect real operating conditions.

To address this, offers a more robust framework. Simscape Multibody, an extension within MATLAB, provides a graphical, physics-based simulation environment where robot components can be modeled as rigid bodies and assembled using mechanical joints and constraints. In the paper by Lê Ngọc Trúc et al., the authors begin by reconstructing the geometry of the IRB 120 using Autodesk Inventor. Each link is designed with accurate dimensions, mass properties, and inertial parameters derived through physical analysis tools in the CAD software. These detailed CAD models are exported and imported into Simscape, forming the foundation of a high-fidelity mechanical system.

Within Simscape, the robot is assembled as a multibody system using revolute joints to reflect the 6-DOF structure of the IRB 120. Unlike traditional Simulink models, where signals represent abstract variables, Simscape models represent actual mechanical behavior through forces, torques, constraints, and transformations. Each joint is configured with rotation axes, motion limits, and can be augmented with physical effects like damping, stiffness, or friction. This physical modeling approach makes it possible to observe how the robot reacts under realistic dynamic loads and controller inputs.

The simulation framework described in the paper proceeds in a comparison is made between the mathematical and quasi-physical models under the same torque inputs. These torques are computed using an inverse dynamics formulation that takes into account the inertia matrix, Coriolis effects, and gravitational terms. Both models are driven by these torques under a prescribed joint trajectory. The results show very close agreement between the two models in terms of joint positions and velocities when friction is not considered. This confirms that Simscape is capable of accurately replicating standard mathematical behavior.

This ability to simulate non-ideal, is one of the greatest strengths of Simscape Multibody. Unlike symbolic models, which would require complex modifications to include friction or motor dynamics, Simscape allows these elements to be easily added using standard library components. Additionally, the visualization of joint forces, actuator torques, and energy consumption can be carried out in real-time, providing a deeper understanding of system behavior and aiding in the design of more robust controllers.

Another significant advantage is the seamless integration with Simulink, enabling the implementation of sophisticated control strategies. PID controllers, trajectory planners, and feedback systems can be connected to the robot’s joints through physical interface blocks. Simulink also allows for the introduction of disturbances, payload changes, and other to test the robustness of the system. The combined Simulink-Simscape environment thus supports a full loop of modeling, simulation, and control design without the need for physical prototypes at early stages. Control algorithms can be tested and tuned without risking hardware damage. The modeling process also promotes interdisciplinary skills in mechanics, dynamics, control theory, and CAD integration.

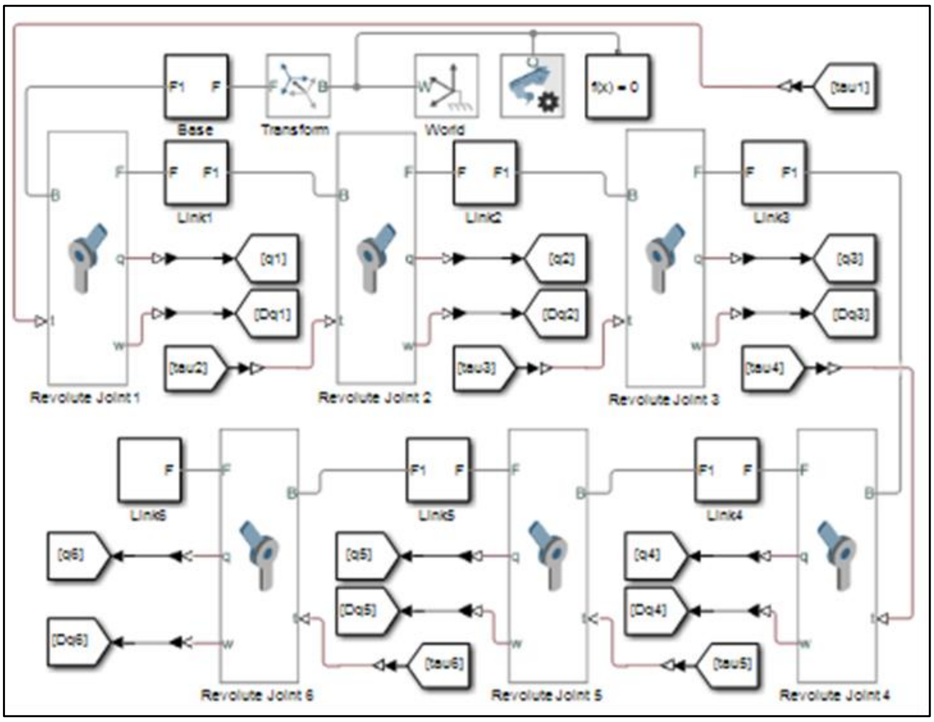

Figure 2 Pseudo-physical simulation model for ABB IRB 120 created with Multibody

In conclusion, the integration of CAD-based modeling, physical dynamics, and control simulation in Simscape Multibody represents a major advancement in robotics modeling. As robotic systems become more complex and mission-critical, will play an increasingly important role in —bridging the gap between theoretical design and practical implementation.

5. Dynamic Simulation and Model Validation

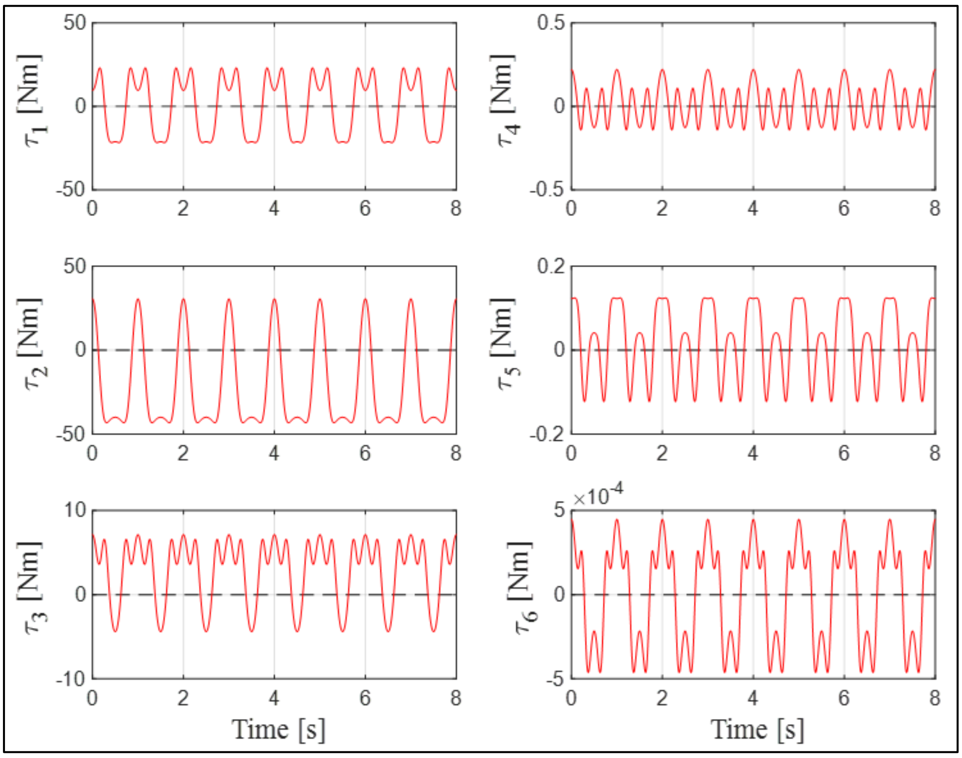

Figure 3 Actuation torques derived from inverse dynamics analysis

The efficacy of a quasi-physical model, specifically in the context of robotic systems, can be robustly demonstrated through a meticulous comparison of its dynamic behavior against a corresponding purely mathematical model. This comparative analysis is particularly pertinent when evaluating the performance of a robotic plant, such as the IRB 120 robot. Within this simulation environment, the crucial input torques are systematically generated through an inverse dynamic algorithm.

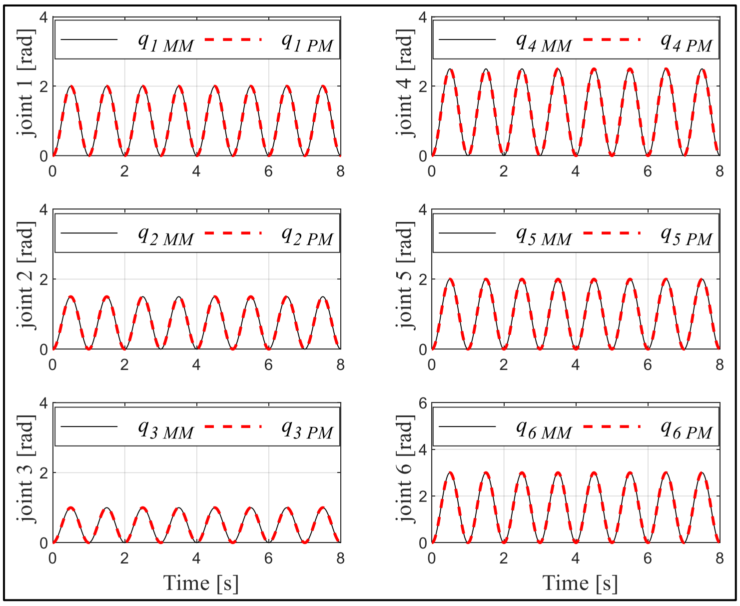

Figure 4 Response comparison between equation-based modeling and multibody simulation approaches

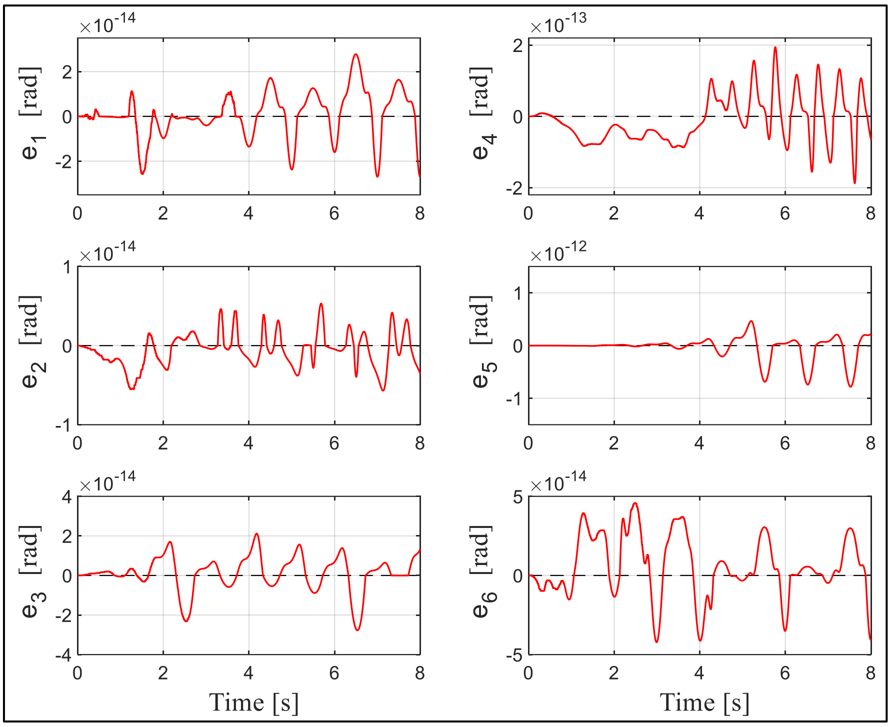

Figure 5 Output errors between mathematical model and multibody simulation responses

In this expression, τ represents the resultant torque vector, which encapsulates the mass distribution and geometric properties of the robot's links.

These calculated torques are subsequently applied in parallel to both the quasi-physical model and the mathematical model of the IRB 120 robot. This parallel application allows for a direct and unbiased comparison of their respective dynamic responses. Observing the outputs of these two distinct models, along with the computed errors between their responses, yields invaluable insights into their fidelity and predictive capabilities. As evidenced by Fig. 4 and Fig. 5, which illustrate the responses of the mathematics model and the quasi-physical model, respectively, a striking degree of convergence is observed. Both models demonstrate a remarkable alignment in their dynamic behavior, exhibiting only marginal tracking errors. These minute discrepancies are often negligible in practical applications and underscore the high degree of accuracy achieved by both modeling approaches.

A pivotal observation arises when the influence of friction is intentionally excluded from the analytical framework. Under such conditions, the observed close correspondence between the dynamic responses of the two models unequivocally validates the equivalence of the quasi-physical model, particularly when it has been constructed using advanced simulation environments like Simscape Multibody, to its theoretical mathematical counterpart. This finding is of significant practical consequence. It implies that the quasi-physical model can effectively serve as a viable and reliable alternative to the more abstract mathematical model for a wide range of robot simulation tasks.

The implications of this equivalence are profound for robotic system design and analysis. Utilizing a quasi-physical model offers several tangible benefits, including the ability to incorporate realistic physical parameters, visualize complex interactions, and conduct comprehensive simulations that more closely mirror. This approach can significantly reduce the need for extensive physical prototyping, thereby accelerating the development cycle and optimizing design iterations. The ability to switch between mathematical and quasi-physical models depending on the specific simulation requirements provides engineers with enhanced flexibility and a more powerful toolkit for understanding and predicting robot behavior. Therefore, the confirmed equivalence ensures that sophisticated simulations can be performed with confidence, leading to more robust and efficient robotic systems. The dynamic behavior, as captured by these models, provides a foundation for advanced control strategies and performance optimization.

6. Discussion

The results of the dynamic simulations presented in the previous section provide critical insights into the physical fidelity, behavioral consistency, and modeling flexibility of the Simscape Multibody-based quasi-physical model of the 6-DOF robotic manipulator.

Comparison with Analytical Models: One of the key findings is the consistency between the frictionless simulation results and those obtained from analytical models derived using Newton–Euler dynamics. This confirms that the quasi-physical model preserves the structural integrity and inertial properties of the manipulator as defined by its D–H parameters and CAD-derived geometry. For simple torque inputs, the model produces motion trajectories that match well with symbolic calculations, validating the correctness of the physical assembly.

Value in Control Design and Validation: The modular nature of the Simscape model allowed for straightforward integration of controllers and testing of different actuation strategies. This flexibility makes the model a useful tool not only for theoretical research but also for applied robotics development. Simulations in a quasi-physical environment enable early-stage design validation, risk of hardware deployment errors.

Realism and Extendability: Beyond joint dynamics, the Simscape Multibody environment allows for future extension of the model to include flexible bodies, thermal effects, sensor noise, or real-world. As such, the developed model serves as a baseline digital twin framework that can be incrementally enhanced for different experimental or industrial applications.

In summary, the discussion emphasizes that bridges the gap between theoretical dynamics and real-world robotic operation. It not only matches traditional results under ideal conditions but also outperforms them when simulating non-ideal behaviors. The model proves to be robust, realistic, and scalable, control design and dynamic validation activities in modern robotic system development.

7. Conclusion

This paper presented a comprehensive approach to modeling and simulating a 6-degree-of-freedom industrial robotic manipulator using the Simscape Multibody toolbox in MATLAB/Simulink. The robot model was developed through a quasi-physical methodology that incorporates detailed geometric, inertial, and dynamic properties directly derived from CAD data. The simulation scenarios were conducted to evaluate the model's performance. The results demonstrated high consistency with traditional analytical models under ideal conditions. The modular and extensible nature of the Simscape-based model allowed for flexible integration of sensors, actuators, and control systems, making it a powerful platform for control development, system diagnostics, and virtual prototyping. Overall, the proposed proves to be robust, scalable, and highly adaptable to a wide range of robotic applications. Future work may extend this framework by incorporating flexible body dynamics, sensor feedback loops, and machine learning algorithms for real-time control and optimization.

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