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Research Article

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Forward Kinematic Analysis and Experimental Validation of the 4-DOF Dobot Magician Robotic Manipulator

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Abstract

The integration of desktop robotic manipulators in academic, research and light-industrial environments requires rigorous, mathematically transparent, and experimentally validated kinematic models. This study presents a systematic analysis of the 4-degree-of-freedom (DOF) Dobot Magician manipulator, focusing on theoretical kinematics, dynamics, and experimental validation. Using the classical Denavit-Hartenberg (DH) convention, a forward kinematic framework is developed to successfully map the structural constraints of the robot's hybrid closed-loop parallelogram linkage into an equivalent serial computational model. A virtual rigid-body environment, implemented in MATLAB using the Robotics System Toolbox, simulates end-effector trajectories and spatial configurations. Experimental validation directly compares physical spatial measurements against target Cartesian coordinates derived from both the theoretical mathematical model and the proprietary Dobot Lab software. The results confirm that the proprietary software relies internally on standard classical DH parameters. Furthermore, statistical evaluation reveals a mean absolute positioning error of 11.0 ± 8.6 mm across the workspace, which is attributed to mechanical tolerance stacking, gear backlash, unmodeled link flexibility, and manual metrology limits rather than kinematic formulation errors. By fully removing software abstraction layers, this open-source kinematic foundation enables precise Cartesian trajectory planning, advanced non-linear control, and real-time computer vision integration in Industry 4.0 applications.

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1 Introduction

Over the past two decades, robotics has evolved from heavy industrial manufacturing cells toward

compact, multifunctional desktop platforms ([Gonzalez 2024](#); [Islam et al. 2019](#)). Desktop robotic arms serve as a vital bridge in contemporary automation, facilitating diverse applications

such as additive manufacturing, laser engraving, high-precision pick-and-place operations, STEM education, and healthcare automation (DOBOT 2026a; Rante et al. 2025; Nugroho et al. 2023; Brito et al. 2021). By providing open programming interfaces—including Python, MATLAB, and ROS—these platforms enable empirical research into kinematics, trajectory generation, and real-time control algorithms that mirror industrial-scale manipulator dynamics (Avanzato 2020).

The Dobot Magician (Fig. 1) has emerged as a benchmark platform in academic institutions and research laboratories due to its versatile payload-to-weight ratio (500 g maximum payload), 320 mm maximum reach, and competitive cost (Matloob et al. 2025). It offers a safe, accessible alternative to conventional industrial manipulators, which often require expensive safety fencing and dedicated infrastructure (Gonzalez 2024). Furthermore, its support for interchangeable end-effectors—such as pneumatic grippers, vacuum suction modules, writing/drawing kits, and 3D printing hot-ends—enables complex cyber-physical system research under the Industry 4.0 paradigm (Woodside et al. 2021; Brito et al. 2021).

Despite these hardware capabilities, user interaction frequently relies on proprietary, closed-source control software such as DobotStudio or



Fig. 1 Perspective view of the 4-DOF Dobot Magician robotic manipulator equipped with a pneumatic gripper end-effector.

Dobot Lab (DOBOT 2026b, 2021). These software environments function as “black boxes”, masking joint-space mappings and kinematic transformations behind graphical teach-and-playback interfaces (Islam et al. 2019). While this abstraction lowers the barrier for introductory users, it conceals the underlying mathematical principles of kinematic transformation and trajectory planning (Nugroho et al. 2023; Avanzato 2020). Consequently, for advanced applications involving Cartesian space path tracking, vision-guided manipulation, or real-time error compensation, closed-source interfaces severely limit system extensibility. Furthermore, published literature presents conflicting metrics regarding positioning performance: while manufacturer specifications cite a repeatability of ± 0.2 mm, several empirical studies report systemic Cartesian coordinate deviations and coordinate frame drifts following

system initialization (Nugroho et al. 2024; Hagen and Rieke 2023).

To address these challenges, this paper presents a complete, open-source, and mathematically rigorous forward kinematic model of the Dobot Magician manipulator. The primary contributions of this work are:

1. A complete 7-frame classical Denavit-Hartenberg (D-H) formulation that incorporates base offsets, joint transformations, tool flanges, and end-effector extensions while accounting for the closed-loop parallelogram linkage constraint.
2. Development of a full virtual rigid-body simulation environment in MATLAB;
3. Systematic experimental validation across twenty operational joint configurations comparing analytical predictions, native software outputs, and physical ground-truth measurements.

2 Mechanical Architecture and Kinematic Modeling

Desktop robotic manipulators generally employ serial, parallel, or hybrid mechanical architectures depending on payload and stiffness requirements (Malla and Shanmugavel 2024). The Dobot Magician features a hybrid mechanical architecture combining a 1-DOF revolute base pedestal with an articulated 3-DOF planar four-bar parallelogram

linkage, as illustrated in Fig. 2 (DOBOT 2026a).

This specific structural arrangement mechanically constrains the pitch orientation of the end-effector, forcing the tool flange to remain strictly perpendicular to the ground plane, regardless of the radial displacements of the shoulder and elbow joints (Gonzalez 2024). By concentrating the mass of the stepper motors closer to the stationary base, this architecture significantly minimizes the inertia of the moving links, thereby enhancing overall system rigidity and dynamic responsiveness.

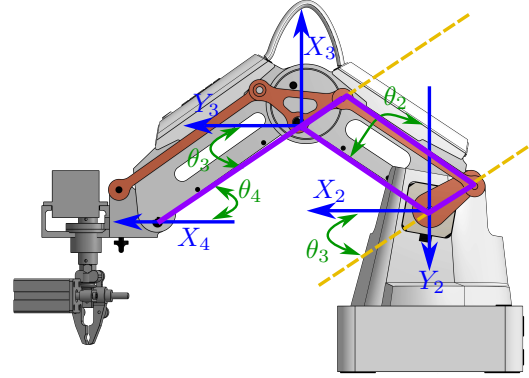


Fig. 2 Kinematic coupling between the shoulder (θ_2), elbow (θ_3), and wrist (θ_4) joints via the mechanical parallelogram linkage.

Although the physical structure of the robot contains closed-loop mechanical chains, standard computational modeling environments require the simplification of such hybrid structures into equivalent open serial chains (Malla and Shanmugavel 2024). In this serial formulation, the passive mechanical wrist joint (θ_4) acts as an unactuated, mathematically dependent variable of the preceding shoulder (θ_2) and elbow (θ_3) positions. This

rigid mechanical constraint dictates that the angular offsets of the wrist counteract the sum of the preceding joint rotations to maintain a strict parallel orientation to the global horizontal resting surface.

2.1 Physical Dimensions and Technical Specifications

The manipulator structure is constructed from 6061-T6 aluminum alloy and high-strength engineering plastics (DOBOT 2026a; Nugroho et al. 2023). Figure 3 illustrates the structural link dimensions and kinematic coordinate definitions.

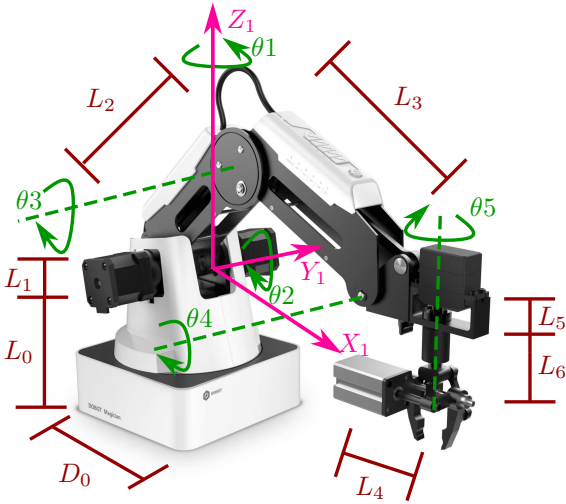


Fig. 3 Structural dimensions, link lengths, and joint coordinate frame assignments for the Dobot Magician.

Tables 1 and 2 detail the technical specifications, physical dimensions, and joint motion constraints.

Table 1 Technical specifications and link dimensions of the Dobot Magician.

Parameter	Notation	Value
Maximum Payload Capacity	-	500 g
Maximum Radial Reach	-	320 mm
Base Width	D_0	158 mm
Base Pedestal Height	L_0	130 mm
Shoulder Flange Thickness	L_1	8 mm
Rear Arm Length / Shoulder	L_2	135 mm
Forearm Length / Elbow	L_3	147 mm
Wrist Link Length	L_4	59.7 mm
Tool Flange Thickness	L_5	8 mm
Pneumatic Gripper Tool Length	L_6	74 mm
Controllable Joint Axes	-	four ¹

¹The controllable joint axes $\theta_1, \theta_2, \theta_3, \theta_5$ represent active stepper motor commands, whereas the passive wrist angle (θ_4) depends on the shoulder (θ_2) and elbow (θ_3) positions.

Table 2 Joint motion range and velocity limits.

Joint Axis	Motion Range	Maximum Speed
Base Pan (θ_1)	$-90^\circ \sim +90^\circ$	
Shoulder Pitch (θ_2)	$0^\circ \sim 85^\circ$	$320^\circ/\text{s}$
Elbow Pitch (θ_3)	$-10^\circ \sim +90^\circ$	
Servo Wrist Roll (θ_5)	$-90^\circ \sim +90^\circ$	$480^\circ/\text{s}$

2.2 Classical Denavit-Hartenberg Parameterization

The forward kinematic mapping from joint space $\theta = [\theta_1, \theta_2, \theta_3, \theta_4, \theta_5]^T$ to Cartesian task space $P = [p_X, p_Y, p_Z]^T$ was formulated using the classical Denavit-Hartenberg convention (Nguyen et al. 2021; Spong et al. 2006). Figure 4 illustrates the assigned coordinate frames $\{0\}$ through $\{7\}$. The origin of the base reference frame $\{0\}$ is placed at the table mounting surface ($Z = 0$), while Frame $\{1\}$ is displaced vertically by $L_0 = 130$ mm. This shifted origin $\{1\}$ corresponds exactly to the

internal Cartesian coordinate system utilized by the native Dobot Lab software.

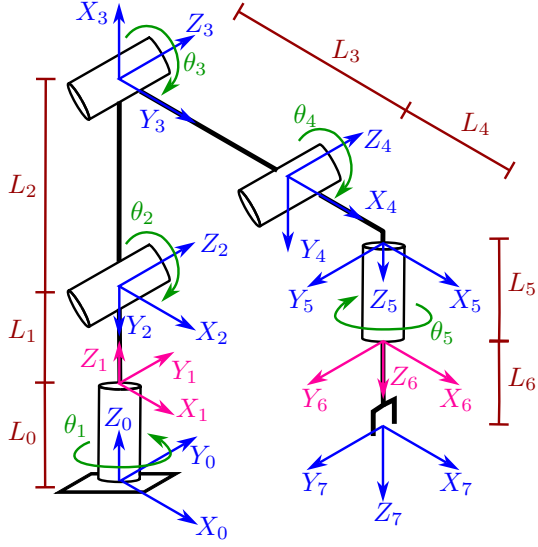


Fig. 4 Complete 7-frame classical Denavit-Hartenberg coordinate assignment for the Dobot Magician manipulator.

The four classical D-H parameters for link n are defined as:

1. r_n : Link length (distance along X_n from Z_{n-1} to Z_n);
2. α_n : Link twist (angle around X_n from Z_{n-1} to Z_n);
3. d_n : Link offset (distance along Z_{n-1} from X_{n-1} to X_n);
4. q_n : Joint angle (angle around Z_{n-1} from X_{n-1} to X_n).

The complete classical DH parameter matrix governing the transformation from the table base Frame $\{0\}$ to the Tool Center Point (TCP) Frame $\{7\}$ is presented in Table 3.

Letting $c_{q_n} = \cos q_n$, $s_{q_n} = \sin q_n$, $c_{\alpha_n} = \cos \alpha_n$ and $s_{\alpha_n} = \sin \alpha_n$, the homogeneous transformation matrix T_n^{n-1} mapping frame $\{n\}$ to frame $\{n-1\}$ is expressed as:

$$T_n^{n-1} = \begin{bmatrix} c_{q_n} & -s_{q_n} c_{\alpha_n} & s_{q_n} s_{\alpha_n} & r_n c_{q_n} \\ s_{q_n} & c_{q_n} c_{\alpha_n} & -c_{q_n} s_{\alpha_n} & r_n s_{q_n} \\ 0 & s_{\alpha_n} & c_{\alpha_n} & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The cumulative transformation matrix T_1^6 mapping the mounting flange face (frame $\{6\}$) relative to the displaced base reference plane (frame $\{1\}$) is obtained via matrix multiplication:

$$T_1^6 = T_1^2 \cdot T_2^3 \cdot T_3^4 \cdot T_4^5 \cdot T_5^6 = \left[\begin{array}{c|c} \mathbf{R}_1^6 & \mathbf{P}_1^6 \\ \hline 0 & 0 & 0 & 1 \end{array} \right] \quad (2)$$

Evaluating Eq. (2) yields the closed-form Cartesian position coordinates $[p_X, p_Y, p_Z]^T$ of the tool flange face relative to frame $\{1\}$:

$$p_X = (L_2 \sin \theta_2 + L_3 \cos \theta_3 + L_4) \cos \theta_1 \quad (3)$$

$$p_Y = (L_2 \sin \theta_2 + L_3 \cos \theta_3 + L_4) \sin \theta_1 \quad (4)$$

$$p_Z = L_1 + L_2 \cos \theta_2 - L_3 \sin \theta_3 - L_5 \quad (5)$$

Equations (3)–(5) provide the explicit mathematical link between input joint angles and end-effector spatial coordinates. Furthermore, when evaluating the Tool Center Point (TCP) at the

Table 3 Classical Denavit-Hartenberg (D-H) parameters for the Dobot Magician.

Link (n)	r_n (mm)	α_n (rad)	d_n (mm)	q_n (rad)	Description / Joint
1	0	0	$L_0 = 130$	0	Fixed Base Offset Frame $\{0\} \rightarrow \{1\}$
2	0	$-\pi/2$	$L_1 = 8$	$q_1 = \theta_1$	Base Pan Rotation (Joint 1)
3	$L_2 = 135$	0	0	$q_2 = -\pi/2 + \theta_2$	Shoulder Pitch (Joint 2)
4	$L_3 = 147$	0	0	$q_3 = \pi/2 - \theta_2 + \theta_3$	Elbow Pitch (Joint 3)
5	$L_4 = 59.7$	$-\pi/2$	0	$q_4 = \theta_4 - \theta_3 = -\theta_3$	Wrist Parallelism Offset (Joint 4)
6	0	0	$L_5 = 8$	0	Fixed Tool Flange Face
7	0	0	$L_6 = 74$	$q_5 = \theta_5$	Tool / Gripper Roll (Joint 5)

tip of the pneumatic gripper (frame $\{7\}$), the tool extension length L_6 is added along the local Z -axis, modifying p_z to:

$$p_Z^{\text{TCP}} = L_1 + L_2 \cos \theta_2 - L_3 \sin \theta_3 - L_5 - L_6 \quad (6)$$

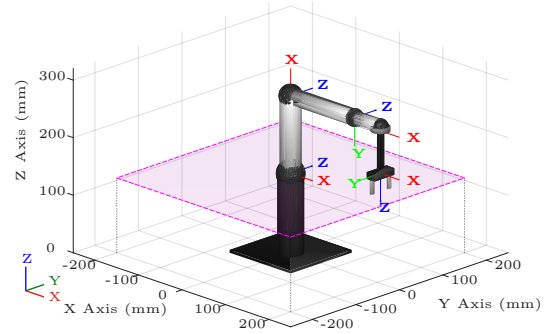
3 Computational Simulation Environment

The kinematic architecture was implemented in MATLAB using the Robotics System Toolbox to create a computational rigid-body model¹. The manipulator is structurally modeled as a `rigidBodyTree`.

The simulation environment programmatically builds the robot structure using the parameters defined in Table 3. Graphical visuals—including parametric cylinders for arm links, spheres for revolute joints, and bounding boxes for the pneumatic gripper—are attached to each body node.

¹The complete open-source MATLAB scripts developed in this study are available at: https://github.com/gadilsoncandido/dobot_magician

Figure 5 illustrates the virtual robot rendering in its default home posture ($\theta_1 = \theta_2 = \theta_3 = \theta_5 = 0^\circ$).

**Fig. 5** MATLAB virtual rigid-body simulation of the Dobot Magician at the home position ($\theta_1 = \theta_2 = \theta_3 = \theta_5 = 0^\circ$).

Figures 6 and 7 demonstrate the orientation-locking behavior of the end-effector during independent shoulder ($\theta_2 = 30^\circ$) and elbow ($\theta_3 = 30^\circ$) motions.

4 Experimental Validation Protocol

An experimental test bench was developed to evaluate positioning fidelity across the derived D-H model, the native Dobot Lab software, and the physical hardware. The apparatus comprised:

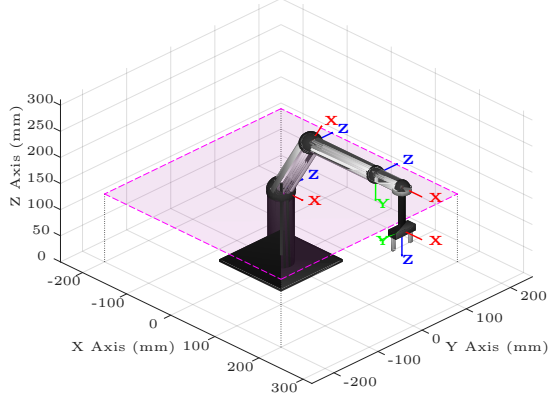


Fig. 6 Virtual simulation for $\theta_1 = \theta_3 = \theta_5 = 0^\circ$ and $\theta_2 = 30^\circ$. Flange position relative to frame $\{1\}$: $X = 274.20$ mm, $Y = 0.0$ mm, $Z = 116.91$ mm.

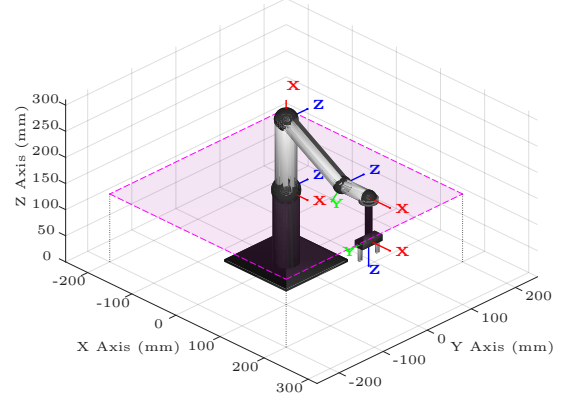


Fig. 7 Virtual simulation for $\theta_1 = \theta_2 = \theta_5 = 0^\circ$ and $\theta_3 = 30^\circ$. Flange position relative to frame $\{1\}$: $X = 187.01$ mm, $Y = 0.0$ mm, $Z = 61.50$ mm.

1. A Dobot Magician manipulator equipped with a calibrated fine-point writing tool;
2. A level surface lined with precision grid paper (1.0 mm resolution);
3. A digital caliper (± 0.02 mm accuracy) and a precision steel rule;
4. A workstation running Dobot Lab (v2.4.6) and MATLAB (R2025a).

Twenty distinct joint configurations $(\theta_1, \theta_2, \theta_3)$ were selected across the manipulator's operational workspace, avoiding kinematic singularities and workspace boundaries. In all scenarios, the end-effector height and orientation were determined from the tool flange frame $\{6\}$ relative to the offset base reference frame $\{1\}$. For each configuration:

1. Target joint angles were commanded via Dobot Lab, and the software's internal Cartesian coordinates $\mathbf{P}_{\text{DOBOT}} = [x_{\text{SLAB}}, y_{\text{SLAB}}, z_{\text{SLAB}}]^T$ were recorded.

2. The physical position of the pen tip was marked on the grid target, and its absolute coordinates $\mathbf{P}_{\text{REAL}} = [p_X, p_Y, p_Z]^T$ were measured manually.
3. The identical joint inputs were evaluated using the analytical MATLAB model to compute the theoretical coordinates $\mathbf{P}_{\text{MATLAB}} = [x_{\text{SIM}}, y_{\text{SIM}}, z_{\text{SIM}}]^T$.

Positional fidelity was evaluated using Euclidean distance error metrics:

$$E_{\text{MATLAB}} = \|\mathbf{P}_{\text{MATLAB}} - \mathbf{P}_{\text{REAL}}\|_2 \quad (7)$$

$$= [(x_{\text{SIM}} - p_X)^2 + (y_{\text{SIM}} - p_Y)^2 + (z_{\text{SIM}} - p_Z)^2]^{1/2}$$

$$E_{\text{DOBOT}} = \|\mathbf{P}_{\text{DOBOT}} - \mathbf{P}_{\text{REAL}}\|_2 \quad (8)$$

$$= [(x_{\text{SLAB}} - p_X)^2 + (y_{\text{SLAB}} - p_Y)^2 + (z_{\text{SLAB}} - p_Z)^2]^{1/2}$$

$$E_{\text{SIM}} = \|\mathbf{P}_{\text{DOBOT}} - \mathbf{P}_{\text{MATLAB}}\|_2 \quad (9)$$

$$= [(x_{\text{SLAB}} - x_{\text{SIM}})^2 + (y_{\text{SLAB}} - y_{\text{SIM}})^2 + (z_{\text{SLAB}} - z_{\text{SIM}})^2]^{1/2}$$

$$+(z_{\text{SLAB}} - z_{\text{SIM}})^2]^{1/2}$$

5 Results and Discussion

The complete experimental dataset across all 20 trials—comprising commanded joint angles, software-predicted Cartesian coordinates, analytical MATLAB computations, and physical ground-truth measurements—is detailed in Table 4. The corresponding statistical error distributions for the native software, analytical model, and software-to-simulation discrepancy are summarized in Table 5.

The proposed MATLAB model and the proprietary Dobot Lab software yield virtually identical outputs, with a maximum discrepancy of only 6.48×10^{-3} mm. This negligible difference stems solely from numerical display truncation in the proprietary interface versus IEEE double-precision arithmetic, confirming that the commercial platform employs standard Denavit–Hartenberg (DH) conventions. Conversely, both kinematic formulations exhibit a systematic mean absolute positioning error of 11.0 ± 8.6 mm relative to physical ground-truth measurements.

Unlike industrial manipulators equipped with active kinematic calibration, this low-cost desktop arm is subject to uncompensated tolerance stacking. This variance is primarily driven by gear backlash, gravitational elastic deflection of

structural links and shafts (which systematically reduces the end-effector Z -elevation), and manufacturing deviations from nominal DH parameters. Furthermore, manual measurement uncertainties—such as parallax and grid-alignment tolerances—inherently contribute to the observed variance.

6 Conclusions

This study presented a closed-form forward kinematic model and its experimental validation for the 4-DOF Dobot Magician manipulator. By applying classical Denavit–Hartenberg conventions, the non-linear kinematic coupling inherent to the robot’s parallel linkage architecture was systematically parameterized.

The analytical MATLAB model demonstrated near-exact agreement with the native Dobot Lab software, exhibiting a maximum discrepancy of only 0.0065 mm and effectively validating the proprietary platform’s internal coordinate transformation framework. Physical trials revealed a mean absolute positioning error of 11.0 ± 8.6 mm, which was shown to stem from mechanical backlash, structural link deflection, manufacturing tolerances, and manual measurement uncertainties, rather than analytical inaccuracies in the kinematic formulation.

Table 4 Comparison of commanded joint angles, software predictions, analytical calculations, and physical measurements.

ID	Joint Angles($^{\circ}$)			Dobot Lab Software(mm)			MATLAB Model(mm)			Actual Reading(mm)		
	θ_1	θ_2	θ_3	x_{SLAB}	y_{SLAB}	z_{SLAB}	x_{SIM}	y_{SIM}	z_{SIM}	p_X	p_Y	p_Z
1	0	0	0	206.70	0.0	135.0	206.700	0.0	135.0	209.0	0.0	132.0
2	10	0	0	203.56	35.89	135.0	203.560	35.893	135.0	209.0	25.0	127.0
3	30	0	0	179.01	103.35	135.0	179.007	103.350	135.0	183.0	100.0	132.0
4	60	0	0	103.35	179.01	135.0	103.350	179.007	135.0	109.0	160.0	132.0
5	90	0	0	0.0	206.70	135.0	0.0	206.700	135.0	0.0	205.0	132.0
6	0	30	0	274.20	0.0	116.91	274.200	0.0	116.913	279.0	0.0	117.0
7	0	50	0	310.12	0.0	86.78	310.116	0.0	86.776	314.0	0.0	85.0
8	0	0	30	187.01	0.0	61.50	187.006	0.0	61.500	184.0	0.0	55.0
9	0	0	60	133.20	0.0	7.69	133.200	0.0	7.694	124.0	0.0	12.0
10	30	30	0	237.46	137.10	116.91	237.464	137.100	116.913	242.0	135.0	107.0
11	30	50	0	268.57	155.06	86.78	268.568	155.058	86.776	274.0	153.0	77.0
12	-40	50	0	237.56	-199.34	86.78	237.563	-199.339	86.776	244.0	-190.0	82.0
13	0	20	30	233.18	0.0	53.36	233.178	0.0	53.359	239.0	0.0	47.0
14	0	50	70	213.39	0.0	-51.36	213.393	0.0	-51.358	209.0	43.0	-53.0
15	-10	0	30	184.16	-32.47	61.50	184.160	-32.470	61.50	182.0	-27.0	55.0
16	-20	0	60	125.17	-45.56	7.69	125.167	-45.557	7.694	122.0	-36.0	7.0
17	-30	10	40	169.53	-97.88	38.46	169.525	-97.876	38.459	169.0	-90.0	35.0
18	-15	60	10	310.43	-83.18	41.97	310.429	-83.179	41.974	319.0	-80.0	32.0
19	40	70	20	248.73	208.71	-4.10	248.730	208.709	-4.104	244.0	210.0	-14.0
20	40	20	45	160.73	134.87	22.91	160.729	134.868	22.914	159.0	135.0	17.0

Table 5 Statistical summary of Euclidean positioning errors (in mm).

Metric	Mean Error	Std. Dev.	Min. Error	Max. Error
E_{DOBOT} (Software vs. Physical)	11.0	8.6	3.4	43.3
E_{MATLAB} (Model vs. Physical)	11.0	8.6	3.4	43.3
E_{SIM} (Software vs. Model)	3.59×10^{-3}	1.89×10^{-3}	0.00	6.48×10^{-3}

The validated open-source kinematic model and simulation routines provide a robust foundation for downstream research, including closed-form inverse kinematics, trajectory optimization, visual servoing, and real-time algorithmic error compensation for low-cost desktop manipulators.

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