EXPLORATION OF THE INVERSE AND FORWARD KINEMATICS OF A TWO-LINK ROBOT ARM USING MATLAB

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This contribution focuses on solving the inverse and forward kinematics in the kinematic analysis of a two-link manipulator model. It involves determining the trajectory of the end effector through fifth-degree polynomial interpolation. Furthermore, given initial and final arm angle values, it computes not only the end effector trajectory but also the angular parameters of individual actuators in both arms. Additionally, it calculates the variations of angular parameters such as rotation angle, angular velocity, and angular acceleration in each kinematic pair. The direct kinematics task is utilized to define the manipulator's workspace. The task is carried out using Matlab software, and the results are presented in the form of graphs and tables.

KEYWORDS

Computer simulation, robot, kinematics, forward, inverse, trajectory, workspace, Matlab

1 INTRODUCTION

The present era has brought about widespread utilization of robots in the operational processes of manufacturing enterprises. They can be advantageously employed in environments detrimental to human health. Additionally, they serve as a substitute for repetitive human tasks or in operations demanding precision in the manufacturing process. The article showcases a methodology for kinematic analysis of a two-link robotic arm model on a fixed base. The two-link manipulator arm is affixed to the bottom fixed part by a rotational joint and comprises two members performing rotational motion. The analysis is conducted using the Matlab program. We are interested in examining the motion of the manipulator arm's end effector. Profiles of angular parameters in kinematic pairs are obtained. The trajectory of the end effector is determined as a function of time, along with other kinematic dependencies.

Industrial robots are composed of bodies that form various types of kinematic chains. These typically consist of mechanisms of robots and manipulators, which, from a kinematic perspective, represent open or mixed kinematic chains. When two bodies of a robot's kinematic chain are interconnected in a way that restricts the movement of one relative to the other, they form a kinematic pair. This involves a mutual connection through a joint. In robotics, translational or rotational kinematic pairs are most commonly encountered, as observed in problem-solving within the works of authors [Vagas 2011, Virgala 2012, Bozek 2014, Mikova 2016, Carbone 2016, Papacz 2018]. This contribution showcases the utilization of computer programs in the kinematic analysis of multi-link robotic systems. The authors draw inspiration from the works of [Spong 2004, Craig 1983, Duysinx 2004, Mikova 2014, Serrano 2015], and others.

Various analytical kinematic methods, geometric methods, and experimental methods are employed in solving kinematics. These methods are complemented by computer simulations from numerous available programs, offering more detailed and illustrative insights into the behavior of robot mechanisms in the manufacturing process. They provide information about kinematic parameters of the system at the desired moment of robot mechanism operation. The issues of computer simulation of robots in Matlab and other programs are addressed in works by authors [Tedeschi 2015 & 2017, Semjon 2016 & 2020, Dyadyura 2021, Lestach 2022, Trojanova 2021, Hroncova 2022 & 2023].

2 ANALYTICAL METHODS

Analytical methods, including analytical geometry, tensor and matrix calculus, complex variables, trigonometric, and vector methods, have been explored in works by [Garcia 2015, Virgala 2014, Holubek 2014].

Nowadays, with the advancement of computer technology, experimental methods linked with computer systems are utilized. Parameters of motion during the operation of mechanisms can be measured, thereby enhancing measurement accuracy, as demonstrated in works by [Nikitin 2022, Peterka 2020, Pirnik 2016, Hargas 2015]. Matrix methods employed in kinematics, with their compact and illustrative matrix representation, are suitable for computer-based applications and are commonly used today. They are conducive to numerical methods applied on computers. Kinematic analysis is addressed in the scholarly works of [Hroncova 2012a,b & 2019, Frankovsky 2013]. Subsequent chapters explore the utilization of simulation program Matlab/Simulink in the kinematic analysis of robot structures, as also referenced in the works of authors such as [Karban 2006].

In the following sections of the paper, we will construct a computer model and subsequently determine the trajectory of the robot's end effector during its motion. Initially, the inverse kinematics problem will be addressed, followed by the forward kinematics problem, as demonstrated in works by [Virgala 2012].

3 MODEL OF A MANIPULATOR WITH A TWO-LINK ROBOTIC ARM

In kinematic analysis, we encounter the theory of simple open kinematic chains when examining various manipulators and robots, which are often structured around these chains. The next chapter will focus on the mechanical system of a two-link manipulator. This type of robotic arm can be found as part of multi-link robots with a fixed base, as depicted in Fig. 1. The mechanical system of the two-link manipulator we're discussing represents an open kinematic chain.

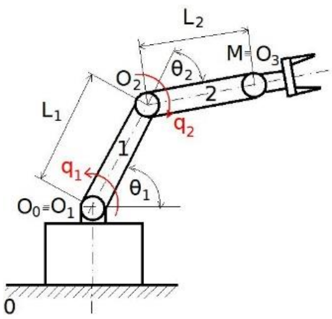

Figure 1. A two-link robotic arm on a fixed base

The manipulator model in Fig. 2 demonstrates the range of motion of the end effector during robot operation.

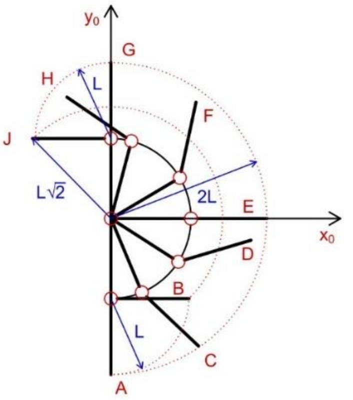

Figure 2. The movement of a two-link robotic arm

The next section will address the inverse and forward kinematics of the motion of two arms illustrated in Fig. 3.

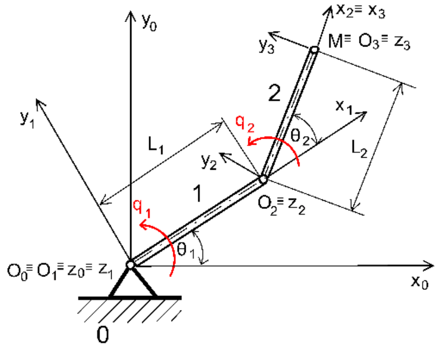

Figure 3. A two-link robotic arm and generalized coordinates q_1 and q_2 ($q_1 = \theta_1$ a $q_2 = \theta_2$), coordinate system O_0,x_0,y_0, O_1,x_1,y_1, O_2,x_2,y_2

In the following sections, we will plot trajectories during the movement of the end effector at selected points in the workspace. We will also illustrate the workspace and determine the profiles of angular variables at the manipulator joints.

4 THE INVERSE KINEMATICS PROBLEM

We will now solve for the two-link robotic arm with arm lengths L_1=0.35 meters and L_2=0.35 meters. The arm is fixed on a solid base as shown in Fig. 4a). Rotational kinematic pairs are located at points O_1 and O_2, with the rotation angle θ_1 for the first arm and θ_2 for the second arm indicated. When solving the forward kinematic task, the kinematic equations (1) and (2) will determine the position of the end point M[x_M,y_M] given the known angles θ_1 and θ_2 of arms of lengths L_1 and L_2 respectively.

$$x_M = L_1\cos\theta_1 + L_2\cos(\theta_1 + \theta_2) \quad (1)$$
$$y_M = L_1\sin\theta_1 + L_2\sin(\theta_1 + \theta_2) \quad (2)$$

We will use the dimensions of the arms of the model: L_1=0.35 m and L_2=0.35 m. The weights of the arms will be m_1=0.3 kg and m_2=0.3 kg. The endpoint will be denoted as M. The generalized coordinates of the given body system are marked as q_1= θ_1 and q_2= θ_2. The coordinate systems of the two arms are depicted in Fig. 3. We are investigating the motion of endpoint M relative to the reference coordinate system O_0,x_0,y_0,z_0. Link 1, to which the coordinate system O_1,x_1,y_1,z_1 is attached, undergoes rotational motion with rotation angle θ_1 around axis $z_0 \equiv z_1$, where θ_1= θ_1(t), relative to the reference coordinate system. The coordinate system of the second link O_2,x_2,y_2,z_2 is shifted in the direction of axis x_1 by a length of L_1. Link 2 then undergoes rotational motion with rotation angle θ_2 around axis $O_2 \equiv z_2$, where θ_2= θ_2(t). We will determine the motion of point M on link 2 with a length of L_2 relative to the reference coordinate system connected to the base 0.

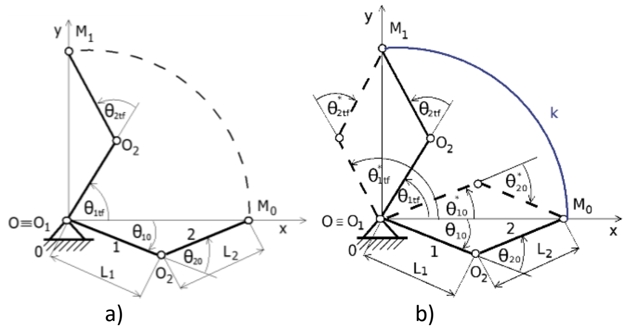

Figure 4. R-R mechanical system with 2° of freedom and a) initial position M_0 and final position M_1 of the point M, b) rotation angle θ_{10} and θ_{20} , θ^*_{10} a θ^*_{20} for initial position of arm and rotation angle θ_{1tf} and θ_{2tf} , θ^*_{1tf} a θ^*_{2tf} for final position of end point

When solving inverse kinematics, we work with the opposite process compared to forward kinematics. We use equations (1) and (2) again. To achieve the desired position of the endpoint of the robotic arm, denoted as x_M, y_M (Fig. 4a), we need to determine the angles of rotation of the joints to position the endpoint M at the desired location. There are typically multiple solutions to this problem, as seen in Fig. 4b). This is a common challenge in robotics because we aim to reach a specific position of the endpoint and thus need to control the joint movements. We will address the problem of finding both angles θ_1 and θ_2 from equations (1) and (2). The first angle θ_1 is between the first arm and the base. The second angle θ_2 is between the first arm and the second arm (Fig. 4). The motion of link 2 and its point M is therefore determined by the angles of rotation θ_1 and θ_2, angular velocities ω_1 and ω_2, and angular accelerations α_1 and α_2. Their values during the motion of endpoint M(t=0) from the initial position at time t=0 to the final position M_1(t=fin) at time t=t_{fin} according to Fig. 4b are calculated in subsequent sections.

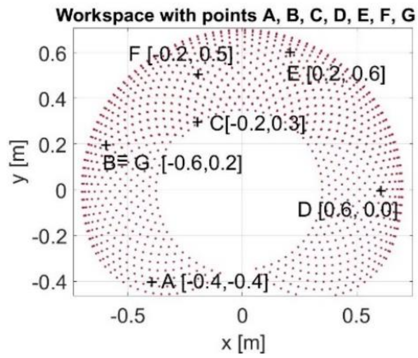

Figure 5. The positions A, B, C, D, E, F and G within the workspace

We will calculate the angles of the arms in the initial position of point M_0 (x_{M0} and y_{M0}) at time t=0 seconds and determine the values of angles θ_{10} and θ_{20}. Then, we will determine the angles of the arms in the final position of point M_{1tf} (x_{M1tf} and y_{M1tf}) at time t=ttf seconds and determine the angles θ_{1tf} and θ_{2tf} according to Fig. 4. The task of determining the angles will be addressed during the movement of the endpoint of the second arm (Fig. 5), among the individual points A, B, C, D, E, F, G, P, Q, whose positions are listed in Table 1 and Table 2.

Table 1. Coordinates x_i, y_i of the points A, B, C, D, E

	A	B	C	D	E
x_i [m]	-0.4	-0.6	-0.2	0.6	0.2
y_i [m]	-0.4	0.2	0.3	0.0	0.6

Table 2. Coordinates x_i, y_i of the points F, G, P, Q

	F	G	P	Q
x_i [m]	-0.2	-0.6	0.7	-0.7
y_i [m]	0.5	0.2	0.0	0.0

By solving the system of equations (1) and (2) for the initial and final positions, we will determine the respective angles of the manipulator's arms as presented in Table 3 and Table 4.

Table 3. Angles when endpoint moves between points A-B, B-C, C-D, D-E

	A-B	B-C	C-D	D-E
θ_{10}	-98.91°	-173.05°	64.69°	-31°
θ_{20}	-72.17°	-50.75°	117.99°	62°
θ_{1tf}	-173.05°	-177.31°	-31°	46.18°
θ_{2tf}	-50.75°	-117.99°	62°	50.75°

Table 4. Angles when end point moves between points E-F, F-G, P-Q

	E-F	F-G	P-Q
θ_{10}	46.18°	151.50°	0°
θ_{20}	50.75°	-79.41°	0°
θ_{1tf}	151.50°	136.18°	180°
θ_{2tf}	-79.41°	50.75°	0°

The trajectories along which the end point will move between the defined points will be determined by solving direct kinematics in the following section.

5 THE FORWARD KINEMATICS

In determining the trajectory of the manipulator's end point M as the arms move at the specified rotation angles, we will employ a fifth-order polynomial. The rotation angle of arm 1 will be assumed to follow the form of a fifth-order polynomial:

$$\theta_1(t) = a_1 t^5 + a_2 t^4 + a_3 t^3 + a_4 t^2 + a_5 t + a_6 \qquad (3)$$

We will assume the rotation angle of arm 2 to be in the form of:

$$\theta_2(t) = b_1 t^5 + b_2 t^4 + b_3 t^3 + b_4 t^2 + b_5 t + b_6 \qquad (4)$$

The initial angles of the arms are known, allowing us to determine the coefficients: $a_6 = \theta_1(t=0)$ and $b_6 = \theta_2(t=0)$. Through differentiation of equations (3) and (4) with respect to time, we derive angular velocity, and its subsequent differentiation yields angular acceleration. The initial and final magnitudes of angular velocity are both zero, a characteristic shared by angular acceleration. Consequently, we establish the coefficients as follows: a_5= 0, a_4= 0, b_5= 0, b_4= 0. By solving this system of equations, we can compute the missing coefficients a_1, a_2, a_3, b_1, b_2, b_3, as listed in Tabs. 5 and 6.

Table 5. The coefficients a_i, b_i of the polynomials, where i=1,2,3

	A-B	B-C	C-D	D-E
a_i	-0.2426	-0.0139	-0.3132	0.2526
	1.2132	0.0696	1.5658	-1.2630
	-1.6176	-0.0928	-2.0878	1.6840
b_i	0.0701	-0.2200	-0.1832	-0.0368
	-0.3505	1.1002	0.9161	0.1841
	0.4673	-1.4670	-1.2215	-0.2455

We subsequently derive the trajectory profile for the angular magnitudes from Tabs. 3 and 4 as the end point traverses individual points with coordinates specified in Tabs. 1 and 2.

The feasibility of this task also warrants evaluation within the working space of the manipulator's dual arms. The workspace (Fig. 5) is influenced by the arm lengths L_1=0.35 meters and L_2=0.35 meters, along with the working range of angular rotations of individual joints $q_1=\theta_1$ and $q_2=\theta_2$ spanning -30° ≤ θ_1 ≤ 200° and -120° ≤ θ_2 ≤ 120°.

Table 6. The coefficients a_i, b_i of the polynomials, where i=1,2,3

	E-F	F-G	P-Q
a_i	0.3447	-0.0501	0.5890
	-1.7233	0.2507	-2.9452
	2.2978	-0.3343	3.9270
b_i	-0.4260	0.4260	0
	2.1299	-2.1299	0
	-2.8399	2.8399	0

Depictions of trajectories y_i=f(xi) for i=1,2,...,7 of the end point transitioning from A to B, then B-C, C-D, and onward to P-Q are showcased in Fig. 6.

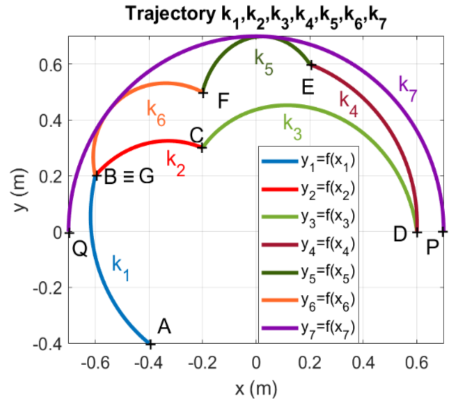

Figure 6. The trajectory components of the end point as it transitions from the initial position at point A to the final position at point B, and subsequently from point B to point C, C-D, D-E, E-F, F-G, and P-Q

Fig. 7 illustrates in the workspace the trajectories of the manipulator's end effector between points A-B, B-C, C-D, D-E, E-F, F-G, including when the arms are fully extended at points P-Q.

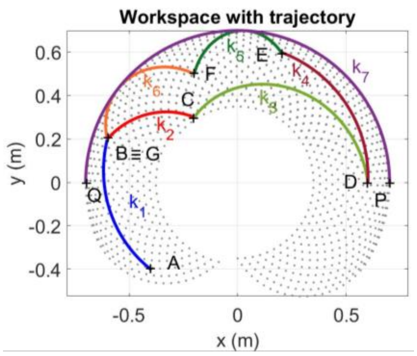

Figure 7. Coordinate pairs (x, y) are plotted for various combinations of θ_1 (-30° to 200°) and θ_2 (-120° to 120°). The trajectory of the end point follows a sequential path from point A to B, then to C, D, E, F, G, and finally from P to Q

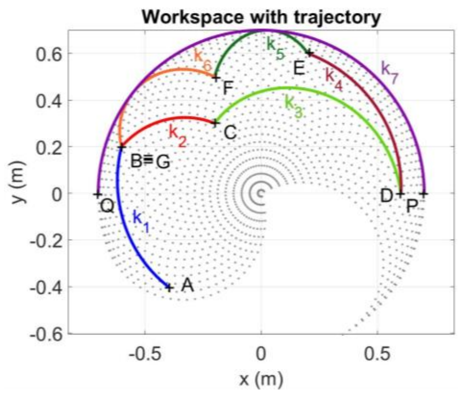

Figure 8. Coordinate pairs (x, y) are plotted for various combinations of θ_1 (-60° to 198°) and θ_2 (0° to 180°). The trajectory of the end point follows a sequential path from point A to B, then to C, D, E, F, G, and finally from P to Q

Fig. 8 depicts the trajectory of the end effector within the workspace, delineated by the constraints on angles θ_1 (-30° to 200°) and θ_2 (-120° to 120°), as it moves sequentially between the designated points A-B, B-C, C-D, D-E, E-F, F-G, and P-Q.

The graphical representation of kinematic parameters obtained by this method will be presented in the following sections of the paper.

6 GRAPHICAL REPRESENTATION OF KINEMATIC PARAMETERS

We can graphically represent the profiles of angular displacement, angular velocity, and angular acceleration over time. The resulting values of kinematic parameters obtained from simulations are processed in Matlab. We are examining the angle of rotation, angular velocity, and angular acceleration of arm 1 and arm 2 as they move from the initial point A to the final point B and subsequent points B-C, C-D, D-E, E-F, F-G, and P-Q. The profiles of angular displacement, angular velocity, and angular acceleration depicted as graphs over time are shown in the following figures. We determined the angles of rotation θ_1 and θ_2 of arm 1 and arm 2 as they move from the initial point A to the final point B, from point B to point C, from point C to point D, from point D to point E, from E to F, and from F to G in Fig. 9.

The values of the angle θ_2 of Link 2 during motion in various segments are provided in Tabs. 3 and 4 in degrees. As expected, the angle values obtained in radians are shown in Fig. 9.

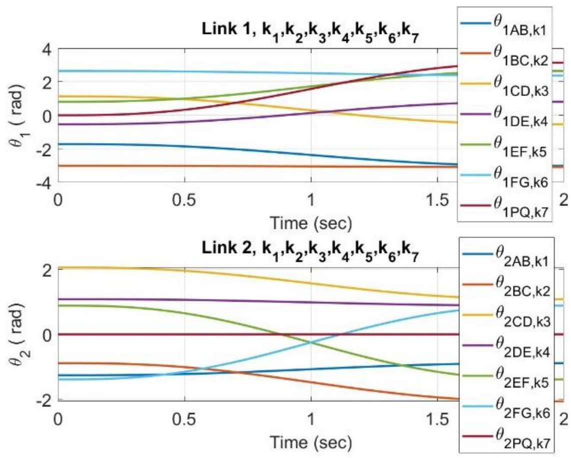

Figure 9. The rotation angles θ_1 and θ_2 of Link 1 (arm 1) and Link 2 (arm 2) as the endpoint transitions from the initial point A to the final point B (A-B), continuing through B-C, C-D, D-E, E-F, F-G and P-Q

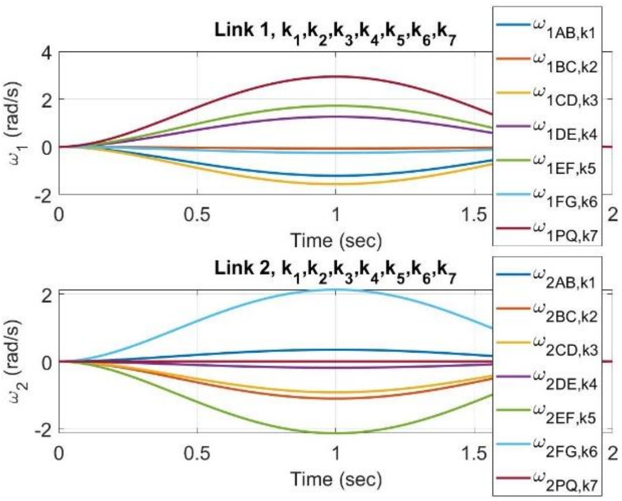

Figure 10. The angular velocity ω_1 of Link 1 (arm 1) and angular velocity ω_2 of Link 2 (arm 2) as it transitions from the initial point A to the final point B (A-B), followed by B-C, C-D, D-E, E-F, F-G and P-Q

Additionally, graphs of kinematic parameters of angular velocity and angular acceleration during the motion of the end point of the arms are displayed. We determined the profiles of angular velocity ω_1 and angular acceleration α_1 of arm 1 during the movement from the initial point A to the final point B, from point B to point C, from point C to point D, and from point D to point E in Fig. 10.

Angular acceleration of arms with lengths L_1=0.35 meters and L_2=0.35 meters is shown in Fig. 11.

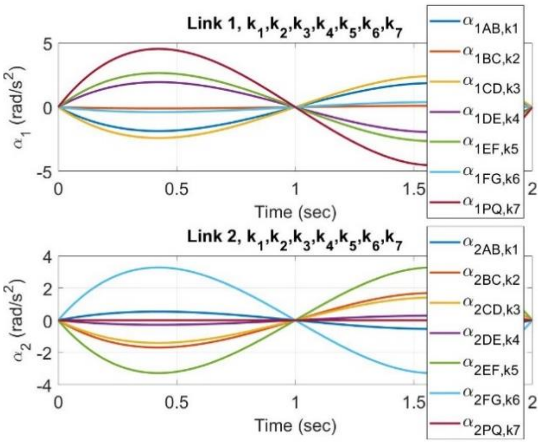

Figure 11. Angular accelerations α_1 and α_2 when end point is moving from the initial point A to the final point B (A-B), followed by B-C, C-D, D-E, E-F, F-G and P-Q

The presented methodology using Matlab allows solving similar robotics tasks both in practice and in teaching the theory of direct and inverse kinematics.

The results obtained from computer simulation are presented in the form of clear graphs.

CONCLUSIONS

The paper presented an analysis procedure for the kinematics of a two-link open kinematic chain robot. The solution was implemented using Matlab.

The model was solved numerically, resulting in obtaining the angular displacement profiles of both arms of the model. Furthermore, the trajectory of the manipulator's end effector was determined at defined points. Subsequently, the profiles of angular rotations, angular velocities, and angular accelerations of both arms were graphically represented. The capabilities of computer simulation in Matlab were demonstrated using manipulator models with a fixed base. Simulation provides immediate information about the parameters of the model being solved. Such simulations afford rapid adjustments to model parameters, with numerical outputs presented through concise graphical formats. Matlab is effectively utilized for simulating the motion of industrial robot and manipulator mechanical systems. The methodology presented herein provides a suitable tool for addressing educational and practical problems.

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