Design and development of a 5-bar 2-DOF Robot

HASSAN ALI 2021-MC-06 **MUHAMMAD SUFYAN** 2021-MC-10 **HAMMAD** 2021-MC-17

Abstract— This project focuses on the design, simulation, and implementation of a 5-bar 2-DOF robot. The aim is to develop a precise and versatile robotic system capable of performing controlled movements in a defined workspace. The project encompasses the development of a Simulink model to simulate the robot's kinematics and dynamics, selection of suitable BLDC motors and controllers for hardware implementation, design and fabrication of the physical robot, and comparison of simulated and hardware performance. Additionally, a touch screen GUI will be developed to provide an intuitive interface for user interaction. The project aims to bridge the gap between theoretical modeling and practical implementation, facilitating advancements in robotics research and industrial automation

Introduction

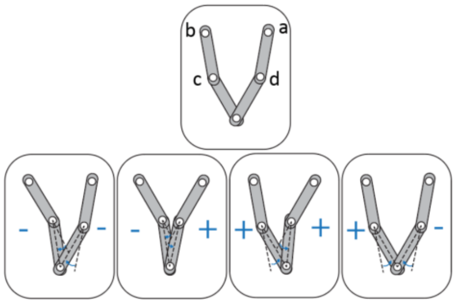
A 5-bar 2 DOF robot is a parallel planar manipulator intended for controlled, accurate movement on a plane. This mechanism provides two distinct degrees of freedom for motion, usually along the X and Y axes. It's made up of five stiff links joined by rotating joints to form a closed kinematic chain. The structure consists of a coupler link that is fastened to the end-effector, a fixed base that has two actuated input links, and extra links that complete the loop. To accomplish desired motions, the robot's kinematics must calculate joint angles (inverse kinematics) or end-effector locations (forward kinematics). Common uses include pick-and-place activities in industrial automation, precise machining in CNC systems, and robotics research in academia. 5-bar 2 Degrees of Freedom (DOF) robots have demonstrated superior repeatability compared to serial robots, as indicated in. This advantage is largely due to three main factors. Firstly, in parallel robots, errors are averaged rather than accumulated, leading to more consistent performance. Secondly, these robots exhibit lower inertia in their movements since their actuators are fixed, resulting in faster operations. Lastly, parallel robots have stiffer structures because the load is distributed across multiple links, enhancing their rigidity and overall stability. This combination of precise, quick, and robust performance makes 5-bar 2-DOF robots particularly advantageous in applications demanding high accuracy and reliability. [1]

OBJECTIVE:

- Develop a Simulink model of a 5-bar 2-DOF robot and drive it in joint space and along a workspace trajectory.
- Select suitable BLDC motors and controllers for manufacturing a hardware robot.
- Design and develop a hardware 5-bar 2-DOF robot and drive it on a trajectory similar to that of the simulated robot.
- Compare the simulated robot's position and velocity with the hardware robot's position and velocity profiles.

ROBOT CONFIGURATIONS:

The five-bar robot has four configuration space regimes: --, -+, ++, and +-. Each sign indicates the sign of the offset angle between the corresponding proximal and distal links. In this robot, the active revolute joints, labeled as 'a' and 'b', are directly controlled by the motors. These joints determine the movement of the robot. The passive revolute joints, labeled as 'c' and 'd', connect the proximal and distal links, allowing for the transmission of motion through the mechanism. The configuration of these joints influences the robot's workspace and the type of motion it can perform, ensuring versatile and precise control over the end-effector's position and trajectory

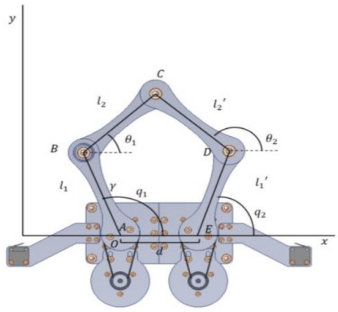


ROBOT CONFIGURATION

Configurations in which one or both of the arms become fully extended cause the end effector to lose at least one of its degrees of freedom. These configurations correspond to kinematic singularities and occur when the robot transitions from one regime to another. To avoid the kinematic singularities in the FK analysis, this example only studies the five-bar robot workspace in the +- regime.

FORWARD KINEMATICS:

The forward kinematic equations have been adapted from Vathan et al [2]. The equations can be used on the program of the robot to evaluate the position of the end effector of the robot for the given angles $q1$ and $q2$



Forward kinematics

The following formulae can be used to determine the end effector's position:

$$x_C = l_1 \cos q_1 + l_2 \cos \theta_1 = d + l_1' \cos q_2 + l_2' \cos \theta_2$$

$$y_C = l_1 \sin q_1 + l_2 \sin \theta_1 = l_1' \sin q_2 + l_2' \sin \theta_2$$

The joints B and D are not actuated by the stepper motors. For that angles $\theta 1$ and $\theta 2$ are dependent and $q1$ and $q2$ are independent:

$$\theta_1 = \sin^{-1}\left(\frac{l_2' \sin\theta_2 += l_1' \sin q_2 - l_1 \sin q_1}{l_2}\right)$$

$$\theta_2 = 2\tan^{-1}\left(\frac{A \pm \sqrt{A^2 + B^2 - C^2}}{B - C}\right)$$

We use the following expressions to find the values of A, B, and C:

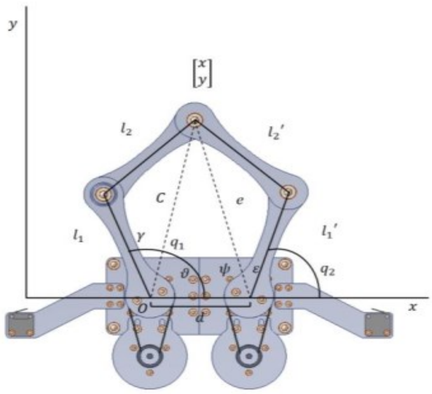
$$A = 2l_2' l_1' \sin q_2 - 2l_1 l_2' \cos q_1$$

$$B = 2l_2' d - 2l_1 l_2' \cos q_1 + 2l_2' l_1' \cos q_2$$

$$C = {l_1}^2 - {l_2}^2 + {l_1'}^2 + {l_2'}^2 + d^2 - l_1 l_1' \sin q_1 \sin q_2 - 2l_1 d \cos q_1 + 2l_1' d \cos q_2 - 2l_1 l_1' \cos q_1 \cos q_2$$

INVERSE KINEMATICS:

The inverse kinematics equations return the values of the angles $q1$ and $q2$ for each value [x, y] of the workspace of the robot These two equations have been obtained using geometric methods.



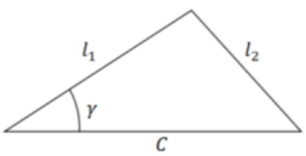
Left side

$$C = \sqrt{x^2 + y^2}$$

$$\vartheta = \tan^{-1}\left(\frac{y}{x}\right)$$

$$q_1 = \vartheta + \gamma$$

Applying the cosine rule:



$${l_2}^2 = {l_1}^2 + C^2 - 2l_1 C \cos(\gamma)$$

$$\gamma = \cos^{-1}\left(\frac{-{l_2}^2 + {l_1}^2 + C^2}{2l_1 C}\right)$$

$$q_1 = \tan^{-1}\left(\frac{y}{x}\right) + \cos^{-1}\left(\frac{-{l_2}^2 + {l_1}^2 + C^2}{2l_1\sqrt{x^2 + y^2}}\right)$$

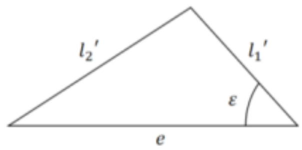
Right side

$$e = \sqrt{(d - x)^2 + y^2}$$

$$\psi = \tan^{-1}\left(\frac{y}{d - x}\right)$$

$$q_2 = \pi - \varepsilon - \psi$$

Applying the cosine rule again:



$${l_2'}^2 = {l_1'}^2 + e^2 - 2l_1' e \cos(\varepsilon)$$

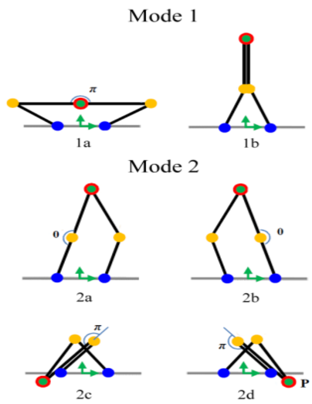
$$\varepsilon = \cos^{-1}\left(\frac{-{l_2'}^2 + {l_1'}^2 + e^2}{2l_1' e}\right)$$

$$q_2 = \pi - \tan^{-1}\left(\frac{y}{d - x}\right) - \cos^{-1}\left(\frac{-{l_2'}^2 + {l_1'}^2 + e^2}{2l_1'\sqrt{(d - x)^2 + y^2}}\right)$$

By default, the robot program operates in mode "+-," but it is possible to modify this using the inverse kinematic functions to achieve the required results.

SINGULARITIES:

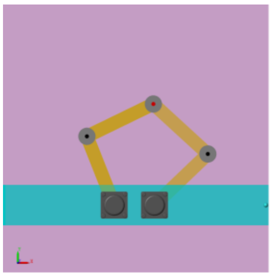
Singularities in the workspace of a 5-bar 2-DOF robot occur when any two links, excluding the grounding link between the motors, become parallel. The position of these singularities varies based on the relative lengths of the robot's links. Mode 2 singularities, involving a driving link, can be navigated out of by activating the associated motor. However, Mode 1 singularities present challenges as they involve two floating links, introducing an indeterminate degree of freedom that cannot be directly controlled by either motor.



SINGULARITY MODES

SIMULINK MODEL:

A 5-bar, 2-DOF robot is modeled and controlled using Simulink. Two stepper motors are used to provide these motors with exact trajectories in order to power the robot's movement. Precise trajectory planning is made possible by the simulation of the robot's kinematics and dynamics using the Simulink model. By directing the robot along predetermined courses inside its workspace, this simulation verifies that the stepper motors are capable of performing the intended movements. Furthermore, the model aids in spotting and avoiding singularities, which can lead to instability and problems with control in the robot's motion.



Running Robot

HARDWARE MAKING METHODOLOGY:

The first step involves creating a detailed 3D model of the 5-bar 2-DOF robot in SolidWorks, a CAD software. This model includes all the robot's components, such as links, joints, and gears. Before moving to physical fabrication, simulations are run in SolidWorks to test the design under various conditions. These simulations help in identifying any potential issues and verifying that the design meets the desired specifications and performance criteria.

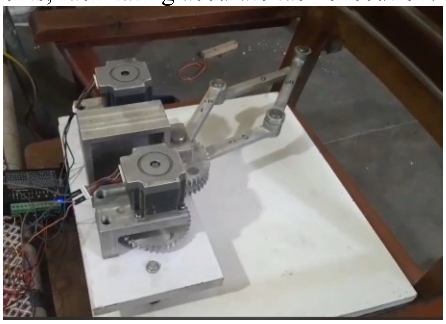
Second step is selection of motor. First BLDC (Brushless DC) motors were considered for their high efficiency and torque capabilities. However, due to the complexity of controlling BLDC motors, stepper motors were chosen instead. Stepper motors offer easier control and are more straightforward to integrate into the system, making them a practical choice for this application.

Two stepper motors are selected to drive the robot's movement. Stepper motors are chosen for their precision and ease of control, which is crucial for the accurate positioning required in a 5-bar mechanism. The stepper motors are integrated into the SolidWorks model, and their performance is simulated to ensure they can achieve the desired movement and torque.

Once the design is validated, the robot's components are manufactured using CNC (Computer Numerical Control) machines. CNC machining allows for high precision and accuracy in creating the robot's parts. Some parts may be produced using casting processes to achieve specific material properties or shapes that are difficult to machine.

The hardware setup includes four gears. Two of these gears are attached to the stepper motors, and the remaining two are connected to the robot's links. This gear configuration is designed to increase the torque available to the robot's links. The gears effectively multiply the force generated by the motors, ensuring that the robot can perform the necessary movements with sufficient power.

In the Arduino IDE, forward kinematics equations are utilized to calculate the motor positions needed to move the robot's end-effector to a specific workspace location. Conversely, inverse kinematics equations determine the joint angles required to achieve a desired end-effector position. These equations enable precise control of the robot's movements, facilitating accurate task execution.



PROTOTYPE

COMPARSION:

Simulink simulations provide valuable insights and predictions about the expected behavior of the robot, the actual performance of the hardware may vary due to various real-world factors. Environmental factors and external disturbances can affect the performance of the hardware robot, which may not be accounted for in the simulation. Factors like friction, backlash, and mechanical tolerances can introduce errors in the real-world operation that are not present in the simulation. n comparing the results between the hardware implementation and the Simulink simulation, several factors need consideration. Firstly, the accuracy and precision of the hardware components, such as the motors, gears, and linkages, play a crucial role in determining the performance of the physical robot. Any deviations or inaccuracies in these components can lead to discrepancies between the simulated and actual movements.

In our case, using gears with the same ratio may have resulted in insufficient torque being transferred to the robot's links. To address this issue, using larger gears attached to the links can help increase torque transmission and improve the robot's performance.

APPLICATIONS:

- **Manufacturing:** Helps assemble products, move parts on assembly lines, and inspect quality in factories.
- **Medical:** Assists surgeons during precise surgeries and helps patients with rehabilitation exercises.
- **Laboratory**: Automates tasks like handling samples and conducting experiments in research labs.
- **Education:** Teaches robotics concepts and programming to students in schools and universities.
- **Home:** Helps with household chores like cleaning floors and organizing items for convenience.

FUTURE IMPLEMENTATION:

In future we have to do

- **Kinematic Optimization:** Enhance robot performance by minimizing joint singularities and improving workspace coverage.
- **Dynamic Analysis:** Improve motion control and stability through dynamic analysis for smoother movements.

- **Sensor Integration**: Integrate sensors for real-time feedback, enabling adaptive control in changing environments.
- **End-effector Design**: Develop specialized end-effectors to maximize robot versatility and effectiveness in diverse tasks.
- **Modular Design**: Implement modular components for easier maintenance, customization, and scalability.
- **Human-Robot Collaboration**: Ensure safe and efficient collaboration between robot and human operators for diverse tasks.
- **Energy Efficiency**: Optimize power consumption with energy-efficient components and control strategies.

DIFFICULTIES:

Robot development presents challenges, especially in motor and gear selection. Picking the right motor means finding the balance between performance and cost. Modeling gears in SolidWorks needs precision and understanding of how they fit together. Choosing gears involves making sure they work well together to move the robot effectively. To tackle these challenges, collaboration and careful thinking are key for success**.**

REFERNCES:

[1] H. Cervantes-Culebro, "Concurrent Design of a 2 Dof Five-Bar Parallel Robot a Hybrid Design of Rigid and Flexible Links," vol. 9, pp. 17450 - 17462, 21 January 2021 . .

[2] L. Vathan.B, "Louis Vathan.B," *Kinematic Analysis of Five-Bar Mechanism in ,* p. 6.