Lab 2: Motor Control, Robot Arm Kinematics and Path Planning

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Abstract

In this report, we document our journey in creating a 2-DOF robot arm using the EV3 Lego Kit and the ev3dev environment. We cover the robot's construction, focusing on its features and the addition of a pen as an end effector.

We highlight the importance of accuracy and repeatability in robot movements and explain how we measured and assessed these qualities. The report explores forward kinematics, explaining how we set the initial robot position and developed a program to control joint angles while calculating where the end effector goes (x, y).

A significant part of our report discusses inverse kinematics, both analytically and through Newton's method. Throughout the report, we present findings based on measurements and observations, offering insights into the challenges and possibilities in robotics and motion control.

Introduction

In the world of robotics, hands-on experience often teaches us the most. This lab project takes us on a journey to build a 2-DOF robotic arm using the EV3 Lego Kit, bridging the gap between theory and practice.

Our main goals include not only physically building the robot arm but also diving into practical aspects like error analysis, planning precise movements, and understanding how the robot behaves in the real world. We've added a pen, marker, or pencil to the arm's end to explore its practical applications.

This report documents our entire adventure. It starts with designing and building the robot arm, delves into how we collected and handled errors, explores how we make the arm move precisely, and dives into the fascinating world of forward and inverse kinematics. We also get our hands dirty with numerical methods like Newton's method to optimize the arm's performance.

Throughout this journey, we've collected measurements, made observations, and analyzed the challenges we've faced. This report is a guide to what we've learned and achieved along the way.

Section 1: Building the 2-DOF robot arm

The construction of our 2-DOF robotic arm was an essential phase in this project, characterized by careful engineering and thoughtful design choices. Below is a comprehensive account of the construction process, considering various design elements and engineering principles:

Design Considerations:

Link Lengths: The robotic arm featured two distinct links, each with unique lengths that significantly influenced its capabilities. The first link extended to 16.8 cm, while the second link measured 10 cm. These dimensions were carefully chosen to strike a balance between achieving the desired workspace and ensuring the arm's effective maneuverability within that space.

Stable Base: The foundation of our robotic arm was pivotal for its structural integrity and precise motion. To ensure these critical aspects, we engineered a robust base featuring a scaffold-like structure. This design incorporated two EV3 bricks securely fastened on one side of the base. This choice provided essential weight for stability while enhancing overall rigidity, enabling the arm to withstand the forces generated during operation.

First Link Framework: Nested within the scaffolded base was a meticulously designed hollow rectangular framework. This framework served a dual purpose – it housed the motor responsible for driving the second link and ensured a robust connection between the two links. The hollow framework also facilitated efficient cable management, contributing to the arm's neat and organized appearance.

Secure Mounting: Ensuring the secure mounting of the first motor was a primary concern. This motor not only powered the first link but also provided crucial support to the second link's operation. The hollow framework crafted for the first link offered an ideal mounting point for the second motor, guaranteeing its stability during operation.

Axle Lengths: We opted for longer-than-required axles for both motors, strategically chosen for multiple purposes. These extended axles featured lower ends positioned as reference points. These reference points were instrumental in two critical aspects of our project:

> *Precise Localization:* They ensured that the base of the robotic arm consistently aligned with the Cartesian coordinates' origin (0,0).
>
> *Calibration:* The extended axles facilitated the confirmation that the arm fully extended along the x-axis, serving as a standard starting position essential for maintaining consistency and precision throughout our experiments.

Second Link: The design of the second link was intentionally kept straightforward, featuring a rectangular shape aligned with our project's requirements. At its terminal end, we incorporated a specialized end effector designed to hold various writing tools, such as a sharpie or pen.

Additional Enhancements:

To further augment the robotic arm's functionality, we integrated several additional enhancements:

Touch Sensor: We introduced a touch sensor that played a pivotal role in recording and marking points of interest. These points were crucial for performing various calculations, including measuring distances, determining the angle between three points, and calculating the midpoint between two marked points.

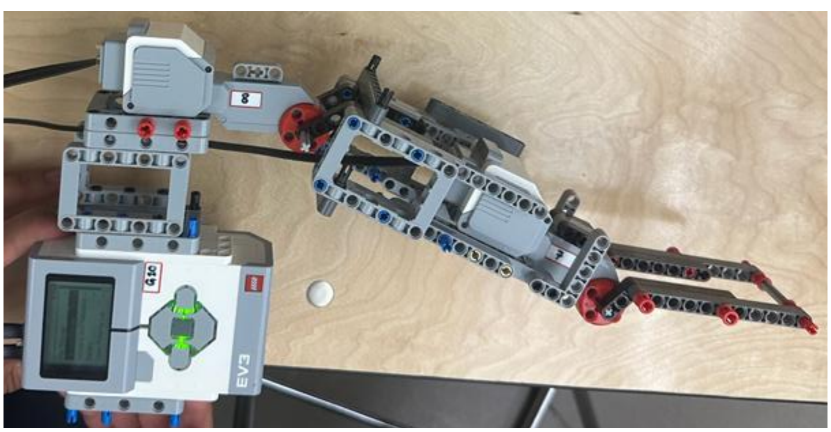
Smooth Movement Support: To ensure smooth movement and additional support, we added a steel ball bearing underneath the first link's termination point. This enhancement contributed to reducing friction, allowing the arm to operate more efficiently and with increased precision.

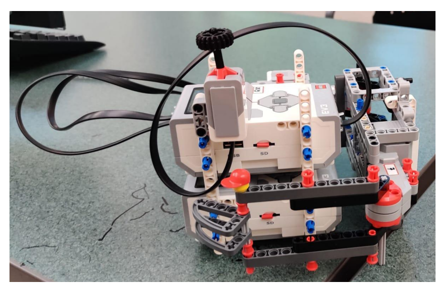
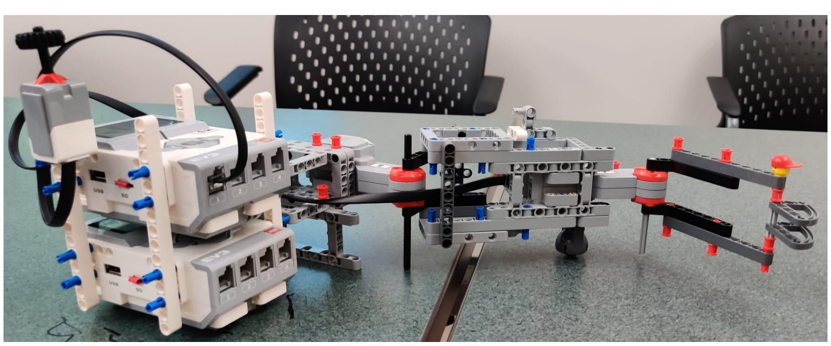
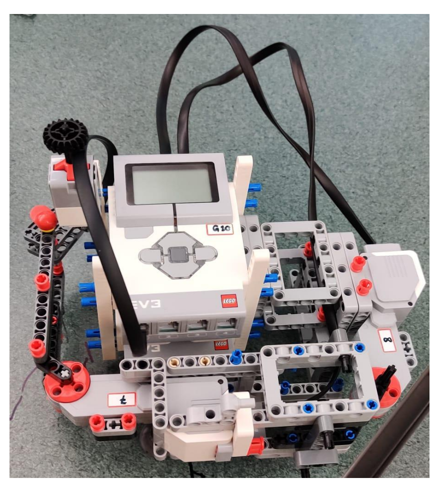
Benefits of the Design:

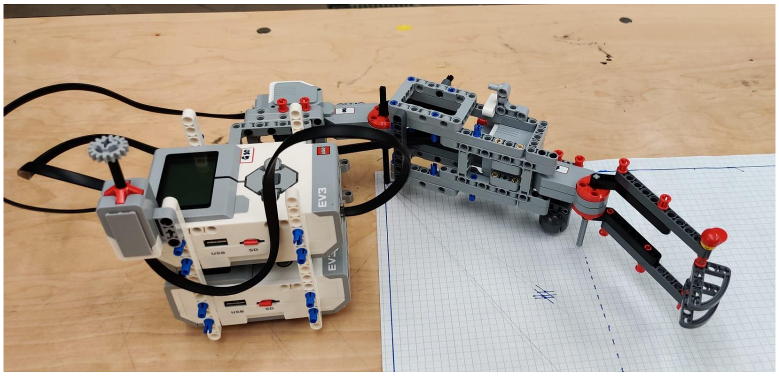
Our meticulous attention to detail in constructing the robotic arm yielded numerous benefits, including:

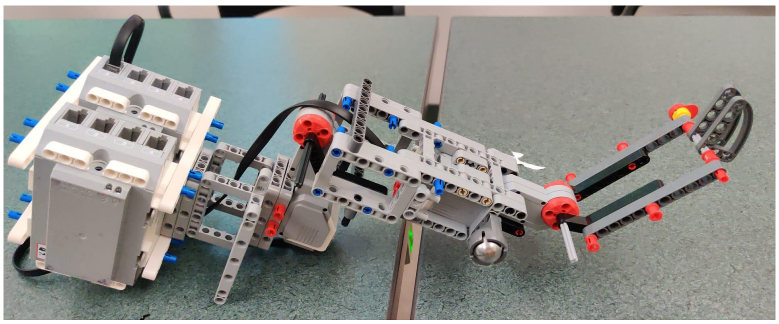
Stability and Strength: The design choices made ensured that the arm could maintain stability even under challenging operating conditions.
Precise Motion Control: The careful engineering of the arm guaranteed precise and repeatable motion, essential for accurate experimentation.
Calibration and Localization: The extended axles and reference points enabled accurate calibration and localization, vital for consistent experimental results.

The pictures below show the features of the robot arm described above;



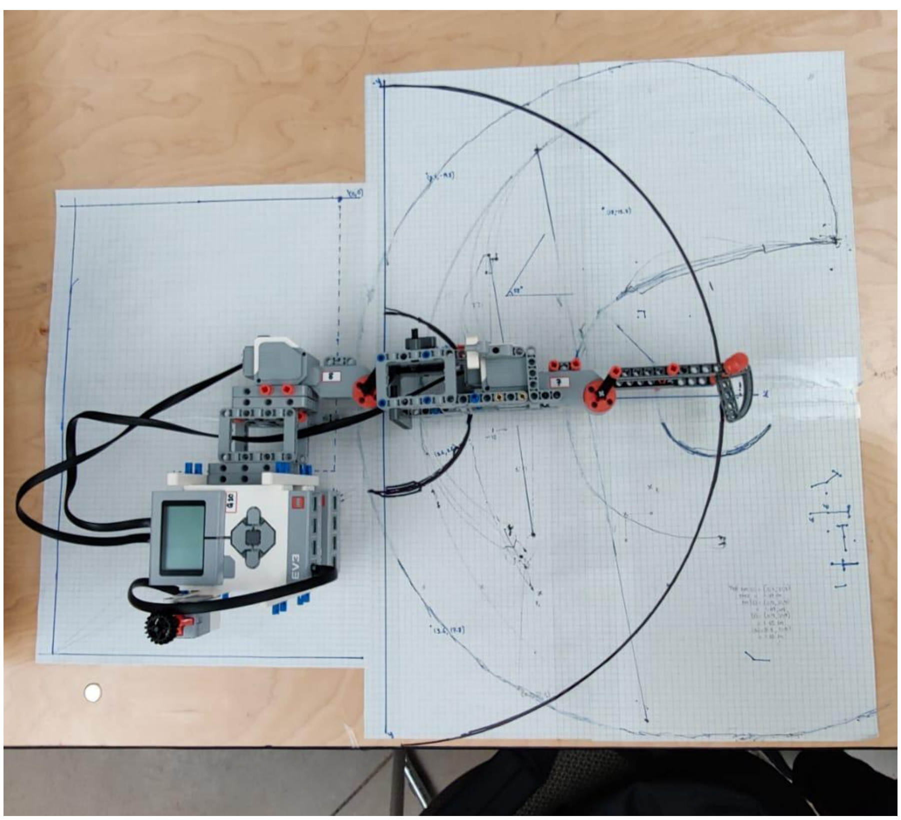








In summary, our robotic arm's construction was characterized by thoughtful design choices, meticulous engineering, and the incorporation of enhancements that significantly contributed to its versatility and functionality. These choices were pivotal in achieving the project's objectives, which relied heavily on the arm's structural integrity, performance capabilities, and advanced features.

The picture below shows the working space of the robot arm, with the arm fully extended along the x-axis and the base of the robot at the (0,0) point.



Section 2: Measuring Accuracy and Repeatability of Arm Movements

In this section, we discuss the procedure and results of our experiments aimed at measuring the accuracy and repeatability of the robotic arm's movements. The program we developed allows us to specify joint angles for the first and second links of the arm and then calculates the actual (x,y) position of the end effector. This information is crucial for assessing the arm's precision in reaching desired positions.

Experimental Setup:

To measure the accuracy of our robotic arm, we used the following setup:

- We set specific joint angles for both the first and second links, simulating various target positions within the arm's workspace.
- For each experiment, we recorded the desired joint angles and expected (x,y) positions based on our knowledge of the arm's kinematics.
- The robot was then instructed to move to the specified joint angles using our program.
- We used the program to calculate the actual (x,y) position of the end effector.

Results and Analysis:

To measure the accuracy/repeatability of arm movements given angles for first and second links							
			Actual (x,y)		Expected (x,y)		
Test run	Link1 angle	Link2 angle	x	y	x	y	Error (cm)
1	45 degrees	45 degrees	11.7	21.9	10.4	22.6	1.476482306
2	45 degrees	45 degrees	11.7	22	10.4	22.6	1.431782106
3	45 degrees	45 degrees	11.9	21.9	10.4	22.6	1.655294536
4	45 degrees	45 degrees	11.5	22.1	10.4	22.6	1.208304597
5	45 degrees	45 degrees	11.7	21.8	10.4	22.6	1.526433752
6	20 degrees	35 degrees	22.3	13.6	21.5	14.3	1.063014581
7	20 degrees	35 degrees	22.4	13.4	21.5	14.3	1.272792206
8	10 degrees	70 degrees	19.1	11.9	18.2	13	1.42126704
9	10 degrees	70 degrees	19.1	12.2	18.2	13	1.204159458
10	30 degrees	30 degrees	20.2	16.5	19.4	17.2	1.063014581
Mean		1.332254516					
Standard deviation		0.189994482					
Variance		0.036097903					

Figure 1: Sample results from accuracy measurement experiments.

The table above provides a summary of our experimental results. For each test run, we specified joint angles, expected (x,y) positions, and recorded the actual (x,y) positions of the end effector. The Euclidean distance error was calculated to quantify the accuracy of the arm's movements. As shown in the table, the error values vary between experiments.

Interpreting Accuracy and Repeatability:

To comprehend the accuracy and repeatability of our robotic arm's movements, it is essential to consider the factors contributing to the observed errors. A substantial portion of these errors can be attributed to two primary sources:

Vertical Play in Motors: The presence of slight but substantial vertical play in the motors can introduce variations in the arm's positioning. This play can lead to deviations from the intended (x,y) coordinates, particularly when transitioning between different joint angles.

Motor Degrees of Freedom: Another significant source of error arises from the motors' approximately 10 degrees of freedom of movement, both clockwise and anti-clockwise, without actually propelling the arm. This inherent flexibility can induce unintended shifts in the arm's configuration, further contributing to discrepancies in positioning.

Section 3: Inverse Kinematics

In this section, we explore the implementation of two distinct solutions for inverse kinematics: a numerical approach utilizing Newton's Method and an analytical approach. These methods are applied to two practical programs: one for positioning the robot end effector at a specified (x,y) location and another for calculating and moving the end effector to the midpoint between two points.

Numerical Approach using Newton's Method

Program for Positioning and identifying the midpoint:

The program for positioning the robot's end effector at a specified (x,y) location begins by prompting the user to move the end effector to the desired point and using the touch sensor. Upon touch sensor activation, the program records the point's coordinates. Then, it instructs the user to reset the arm to extend along the x-axis. Next the program calculates the required link angles and repositions itself to the marked point. In the second part, the program instructs the user to record the two points using the touch sensor. After the user resets the robot to the x axis, it calculates and moves the end effector to the midpoint between the two recorded points using Newton's Method.

Analytical Approach

Program for Positioning:

While the numerical approach relies on iterative methods, the analytical approach leverages mathematical equations to determine joint angles directly based on the desired (x,y) location. This method involves a series of trigonometric calculations, including arctangent functions, to find the necessary joint angles to position the end effector accurately.

Comparison and Analysis

When choosing an approach for solving inverse kinematics problems, such as positioning the robot's end effector, several factors come into play. Here, we delve deeper into the comparison and analysis of the numerical (Newton's Method) and analytical methods:

1. **Computational Complexity:**

    - Numerical Approach (Newton's Method): This method involves an iterative process, which means that it might require several iterations to converge to a solution. While this can handle complex robot structures, it comes at the cost of computational complexity.

    - Analytical Approach: Analytical solutions often provide direct mathematical expressions to compute joint angles. As a result, they tend to have lower computational complexity, making them suitable for real-time or high-speed applications.

2. **Sensitivity to Initial Conditions:**

    - Numerical Approach (Newton's Method): Newton's Method can be sensitive to initial conditions. If the initial guess for joint angles is far from the solution, the method may converge to a local minimum or fail to converge altogether. Our initial link angles have been set to 1 degree.

- Analytical Approach: Analytical methods usually do not require initial guesses. They provide deterministic solutions, ensuring stability and predictability in most cases.

3. **Speed and Predictability:**

    - Numerical Approach (Newton's Method): While it may be slower due to iterations, Newton's Method can handle a wide range of robotic configurations and is suitable for systems with redundancy or complex kinematic chains.

    - Analytical Approach: Analytical solutions are generally faster, as they directly compute joint angles without the need for iterative refinements. However, they are best suited for robots with simpler kinematic structures such as ours.

4. **Convergence Issues:**

    - Numerical Approach (Newton's Method): Newton's Method may face convergence issues, particularly in situations where there are multiple solutions or singularities in the kinematic chain(for example when the initial angles are set to zero degrees). Careful consideration of initial conditions and proper handling of singularities are essential. In our case, we check for zero division error and terminate the loop if a zero division error exists.

    - Analytical Approach: Analytical solutions may not be available for robots with highly complex or irregular structures. In such cases, they may not provide a viable option, and numerical methods become necessary.

5. **Applicability:**

    - Numerical Approach (Newton's Method): This approach is versatile and adaptable to various robotic systems. It can accommodate changes in the robot's configuration or environment, making it suitable for dynamic scenarios.

    - Analytical Approach: Analytical methods are most effective for robots with well-defined and straightforward kinematic structures. They are less adaptable to changes in robot design or environmental conditions.

Conclusion

The choice between the numerical (Newton's Method) and analytical approaches for solving inverse kinematics depends on the specific requirements and constraints of the robotic system. Numerical methods offer flexibility and can handle complex scenarios but require careful initialization and can be computationally intensive. Analytical methods are efficient and predictable but are best suited for robots with simple kinematic structures. A thorough analysis of both approaches enabled us to identify the most appropriate method for our particular robotic application, the analytic method. However, a robot arm with higher degrees of freedom would require numerical methods ensuring optimal performance and precision. Additionally, further research and optimization may lead to hybrid approaches that combine the strengths of both methods for improved efficiency and reliability in inverse kinematics problem-solving.