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ANALYSIS AND OPTIMIZATION OF A MECHATRONIC DESIGN MODEL: CASE OF AN AGRICULTURAL ABB IRB ROBOT 140

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Abstract

This study focuses on analyzing and optimizing the ABB IRB 140 robot for agricultural applications, addressing challenges such as uneven terrain, crop sensitivity, and energy efficiency. A simulation-driven approach was employed using forward and inverse kinematics, trajectory planning, and MATLAB-based validation. The optimized design demonstrated smoother trajectories, reducing unnecessary joint movements, and achieving energy savings of up to 18%. Additionally, economic feasibility analysis revealed a payback period of approximately 1.63 years, highlighting the practicality of deploying the robot in agriculture. This research provides a framework for adapting industrial robots to meet the demands of precision agriculture and sustainable farming practices.

Keywords

ABB IRB 140, Agricultural Robotics, Kinematic Optimization, MATLAB Simulation, Precision Agriculture, Trajectory Planning, Mechatronics in Agriculture.

Contents

Chapter 1

Introduction

1.1 Background

Agriculture is under increasing pressure to meet global food demands while addressing labor shortages and the need for sustainability [1, 2]. Robotic solutions, such as the ABB IRB 140, can automate tasks like planting, harvesting, and crop monitoring [3]. The ABB IRB 140, widely recognized for its precision in industrial applications, has shown potential to revolutionize agricultural tasks, yet its application in this domain remains largely untapped [4].

1.2 Problem Statement

Despite its versatility, the ABB IRB 140 is not optimized for agricultural tasks. Its design is primarily tailored for controlled industrial environments, which poses challenges such as:

- Operating on uneven terrain.
- Handling variability in weather conditions.
- Dealing with the sensitivity of crops to external factors.

These issues limit the robot's performance in agriculture. This research addresses these challenges by focusing on optimizing the robot's kinematics, trajectory planning, and control strategies.

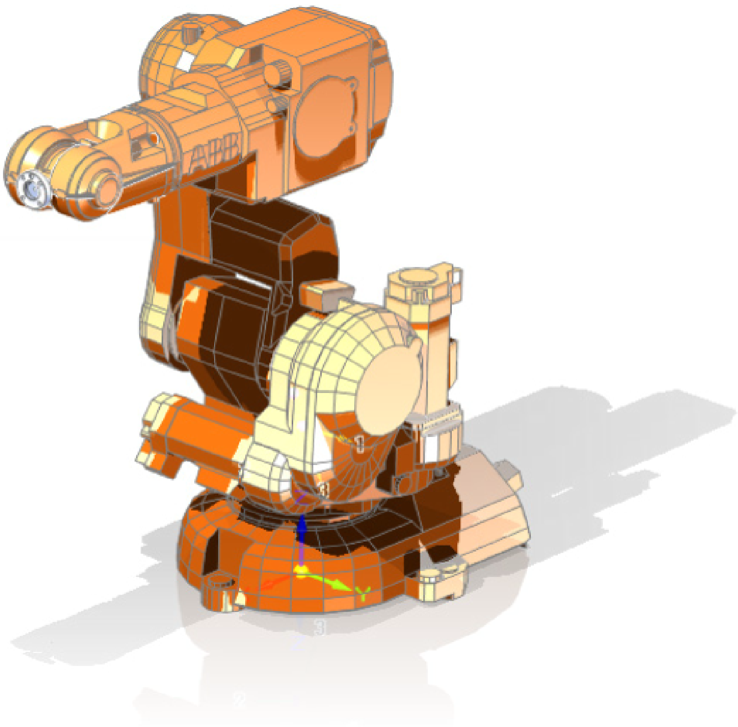

Figure 1.1: ABB IRB 140 robot.

1.3 Objectives

The main objectives of this research are:

- **Analyze the robot's kinematics and performance** for agricultural applications.
- **Develop optimized control strategies** to improve energy efficiency and task precision.
- **Validate improvements** through simulations and comprehensive performance metrics.

1.4 Research Questions

This study aims to answer the following questions:

1. How can the ABB IRB 140's design and control strategies be adapted for agricultural environments?

2. What measurable improvements in energy efficiency and task precision can be achieved through optimization?
3. How reliable are simulation results in predicting the robot's real-world applicability?

1.5 Significance of the Study

This research is significant as it addresses global challenges in agriculture, such as labor shortages, rising food demands, and the need for precision farming. By optimizing the ABB IRB 140, the study aims to contribute to:

- **Enhanced Agricultural Productivity**: Improved yields and reduced operational costs [2].
- **Labor Efficiency**: Robots can take over repetitive tasks, freeing human labor for more complex activities.
- **Sustainability**: Energy-efficient configurations reduce the environmental footprint.

The findings of this study will benefit farmers, agricultural researchers, and the robotics industry, offering a framework for designing intelligent agricultural robots.

1.6 Scope and Limitations

1.6.1 Scope

The scope of this study includes:

- Optimizing the kinematics and control algorithms of the ABB IRB 140 for specific agricultural tasks.
- Simulating agricultural scenarios such as planting, harvesting, and soil sampling.
- Evaluating the robot's performance in terms of energy efficiency, precision, and task completion.

1.6.2 Limitations

The research is limited by:

- **Simulations Only**: Testing is restricted to simulated environments, with no real-world field trials.
- **Ideal Conditions**: Simulations assume ideal conditions, which may differ from actual farming scenarios.
- **Narrow Focus**: The study focuses on specific tasks and excludes broader applications like livestock management.

Future research can expand on these limitations by conducting real-world tests and exploring additional agricultural applications.

Chapter 2

Literature Review

2.1 Overview of Robotic Applications in Agriculture

Robotics has become a cornerstone of precision farming [2], offering solutions to automate tasks like planting, harvesting, and crop monitoring [5]. Several robots have been developed for agriculture, each with unique strengths and limitations [5]:

- **Agrobot SW6010**: Specializes in automated fruit picking using advanced manipulators but is limited to specific crops like strawberries [6] (Figure 2.1).

Figure 2.1: Agrobot SW6010: Designed for strawberry harvesting.

- **Harvest CROO Robotics**: Designed for large-scale harvesting with high efficiency, yet lacks general-purpose adaptability [7] (Figure 2.2).

Figure 2.2: Harvest CROO Robotics: Optimized for large-scale agricultural tasks.

- **ABB IRB 140**: Known for its compact size and high precision, widely used in industrial settings but underutilized in agriculture [4] (Figure 2.3).

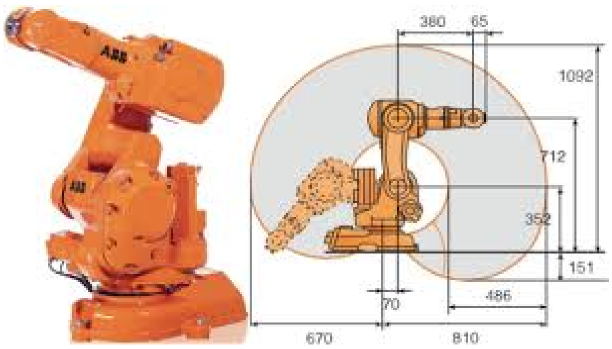

Figure 2.3: ABB IRB 140: An industrial robot with potential for agricultural applications.

While these robots excel in their respective niches, the adaptability of general-purpose robots like the ABB IRB 140 for agricultural applications remains an underexplored domain.

2.2 Comparative Analysis of the ABB IRB 140

The ABB IRB 140 offers several advantages over its counterparts:

- **Precision**: High repeatability of ±0.03 mm makes it suitable for tasks requiring fine manipulation [4].

- **Compact Design**: Its small footprint allows it to navigate tight spaces in row-based planting scenarios [5].
- **Versatility**: Supports multiple end-effectors, enabling diverse tasks like fruit picking and soil sampling [2].
- **Cost-Effectiveness**: Compared to specialized robots, it offers affordability, making it accessible to farmers in developing countries [8].

However, its lack of inherent adaptability to dynamic environments, such as uneven terrain and varying crop conditions, poses challenges for agricultural applications.

2.3 Emerging Technologies and Integration Possibilities

Advances in technology provide opportunities to enhance the ABB IRB 140 for agricultural tasks:

- **Artificial Intelligence (AI)**:
  - Enables real-time decision-making for tasks like obstacle avoidance and path planning [9].
  - Machine learning algorithms can improve task efficiency by learning from repetitive actions.
- **Computer Vision**:
  - Assists in identifying crops, detecting weeds, and ensuring precise placement during planting [10].
  - Real-time image processing can guide the robot's end-effector with high accuracy.
- **Sensor Fusion**:
  - Integrates data from soil sensors, weather monitors, and GPS for adaptive decision-making [11].

– Allows dynamic adjustments to trajectories based on environmental conditions.

2.4 Specific Challenges in Agricultural Robotics

The unique nature of agricultural environments presents several challenges:

- **Soil Variability**:
  - Uneven terrain can affect the robot's stability and precision [5].
  - Requires enhanced control algorithms to maintain end-effector accuracy.
- **Weather Conditions**:
  - Environmental factors like rain, heat, and wind may disrupt operations [2].
  - Protective designs and robust control systems are needed for reliability.
- **Crop Sensitivity**:
  - Sensitive crops such as tomatoes or leafy greens require careful handling to avoid damage [8].
  - Advanced end-effectors with force control mechanisms are essential.

2.5 Kinematic Analysis in Robotic Applications

Kinematics is a critical aspect of robotic design, particularly for precision tasks in agriculture. Previous studies have explored [12]:

- **Forward Kinematics**:
  - Studies focus on using Denavit-Hartenberg (D-H) parameters to model robot motion.
  - Accurate transformation matrices ensure precise end-effector placement.
- **Inverse Kinematics**:
  - Analytical and geometric methods are used to calculate joint angles [5].

– Challenges arise in solving multiple solutions for complex configurations.

These studies highlight the importance of kinematic modeling in optimizing robots for agricultural tasks.

2.6 Research Gap and Opportunities

Although substantial research exists on the ABB IRB 140's applications in industrial settings, its use in agriculture remains underexplored [4]. Key gaps include:

- **Limited Field Studies**: Most research relies on simulations without real-world validation.
- **Lack of Dynamic Adaptability**: Few studies address the robot's ability to handle variable environments.
- **Optimization Techniques**: Minimal focus on energy efficiency and trajectory planning for agricultural scenarios.

This research aims to bridge these gaps by optimizing the ABB IRB 140 for agricultural applications and validating its performance in simulated agricultural tasks.

2.7 Contribution of This Research

This study contributes to the field by:

- Developing a kinematic model tailored for agricultural tasks.
- Optimizing control strategies for energy efficiency and precision.
- Demonstrating the robot's adaptability to agricultural environments through simulation-based validation.

The findings are expected to guide future efforts in integrating robotics into agriculture, addressing challenges, and improving productivity.

Chapter 3

Methodology

3.1 Kinematic Analysis

Kinematics is the foundation of robotic motion [1], describing the relationship between joint variables and the position and orientation of the end-effector. This section provides a detailed mathematical solution for forward and inverse kinematics using the Denavit-Hartenberg (D-H) convention.

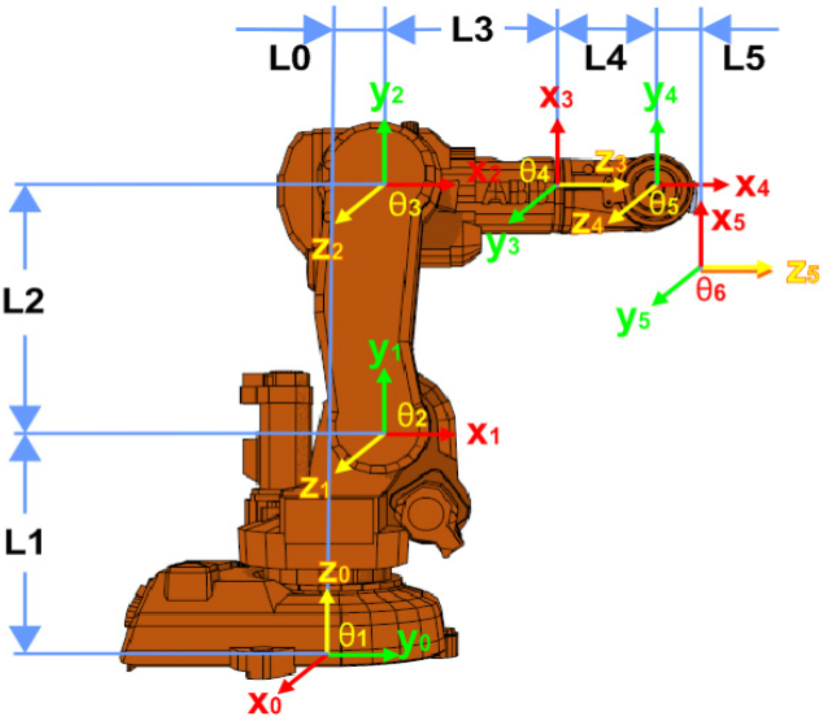

Figure 3.1: Home position and reference frames.

3.1.1 Forward Kinematics

The forward kinematics of the ABB IRB 140 determines the position and orientation of the end-effector in the base frame by sequentially multiplying the transformation matrices of individual joints using the Denavit-Hartenberg (D-H) convention [1, 2].

Transformation Matrix The general D-H transformation matrix for a joint is given as [1]:

$$T_i^{i-1} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_{i-1} & \sin\theta_i \sin\alpha_{i-1} & a_{i-1}\cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_{i-1} & -\cos\theta_i \sin\alpha_{i-1} & a_{i-1}\sin\theta_i \\ 0 & \sin\alpha_{i-1} & \cos\alpha_{i-1} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Individual Joint Transformations For the ABB IRB 140, the D-H parameters yield the following transformation matrices [4]:

1. **From Base to Joint 1 ($^0T_1$):**

$$^0T_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

2. **From Joint 1 to Joint 2 ($^1T_2$):**

$$^1T_2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & a_1 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_2 & -\cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

3. **From Joint 2 to Joint 3 ($^2T_3$):**

$$^2T_3 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & a_2 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4. **From Joint 3 to Joint 4 ($^3T_4$):**

$$^3T_4 = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & 0 \\ 0 & 0 & 1 & d_4 \\ -\sin\theta_4 & -\cos\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

5. **From Joint 4 to Joint 5 ($^4T_5$):**

$$^4T_5 = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin\theta_5 & \cos\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

6. **From Joint 5 to Joint 6 ($^5T_6$):**

$$^5T_6 = \begin{bmatrix} \cos\theta_6 & -\sin\theta_6 & 0 & 0 \\ \sin\theta_6 & \cos\theta_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

End-Effector Position and Orientation The overall transformation matrix is obtained by multiplying the individual matrices [1]:

$$^0T_6 =^0 T_1 \cdot^1 T_2 \cdot^2 T_3 \cdot^3 T_4 \cdot^4 T_5 \cdot^5 T_6$$

Expanding this multiplication yields the position and orientation of the end-effector in terms of θ_1 through θ_6.

Key Results The final position of the end-effector in Cartesian coordinates (x, y, z) and its orientation as rotation matrices (R_{06}) are derived from ${}^0T_6$. These results serve as input for trajectory planning and inverse kinematics.

3.1.2 Inverse Kinematics

Inverse kinematics involves determining the joint variables $(\theta_1, \theta_2, \ldots, \theta_6)$ to achieve a desired position and orientation of the end-effector [2, 12]. For the ABB IRB 140, this calculation uses geometric relationships and ZYZ Euler angles.

End-Effector Pose The end-effector's position and orientation are described by the transformation matrix [5]:

$$
{}^0T_6 = \begin{bmatrix} nx & ox & ax & px \\ ny & oy & ay & py \\ nz & oz & az & pz \\ 0 & 0 & 0 & 1 \end{bmatrix},
$$

where:

- (px, py, pz): Position of the end-effector.
- (nx, ny, nz), (ox, oy, oz), (ax, ay, az): Orientation vectors.

Step 1: Wrist Center Position The wrist center position (x_w, y_w, z_w) is calculated as [10]:

$$
x_w = px - d_6 \cdot ax,
$$

$$
y_w = py - d_6 \cdot ay,
$$

$$
z_w = pz - d_6 \cdot az.
$$

Step 2: Solving for θ_1, θ_2, θ_3 Using geometric relations [1]:

$$
\theta_1 = \arctan\left(\frac{y_w}{x_w}\right).
$$

For θ_2 and θ_3, apply the law of cosines and geometry:

$$\begin{aligned}
r &= \sqrt{x_w^2 + y_w^2}, \\
z'_w &= z_w - d_1, \\
\theta_2 &= \arctan\left(\frac{z'_w}{r}\right) - \arccos\left(\frac{r^2 + z'^2_w - a_2^2 - d_4^2}{2 \cdot a_2 \cdot d_4}\right), \\
\theta_3 &= \arccos\left(\frac{r^2 + z'^2_w - a_2^2 - d_4^2}{2 \cdot a_2 \cdot d_4}\right).
\end{aligned}$$

Step 3: Orientation Angles (θ_4, θ_5, θ_6) The end-effector's orientation matrix ${}^0R_6$ is decomposed using [11]:

$$^0R_6 = R_{03} \cdot R_{36},$$

where R_{03} is derived from θ_1, θ_2, and θ_3, and R_{36} represents the last three joints.

The orientation matrix R_{36} is calculated as:

$$R_{36} = R_z(\alpha) \cdot R_y(\beta) \cdot R_x(\gamma),$$

where α, β, and γ are the ZYZ Euler angles:

$$R_z(\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad R_y(\beta) = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}, \quad R_x(\gamma) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{bmatrix}.$$

The angles are solved as:

$$\begin{aligned}
\theta_5 &= \arctan 2\left(\sqrt{r_{31}^2 + r_{32}^2}, r_{33}\right), \\
\theta_4 &= \arctan 2\left(\frac{r_{32}}{\sin\theta_5}, \frac{-r_{31}}{\sin\theta_5}\right), \\
\theta_6 &= \arctan 2\left(\frac{r_{23}}{\sin\theta_5}, \frac{r_{13}}{\sin\theta_5}\right).
\end{aligned}$$

Step 4: Multiple Solutions Each θ angle may have multiple valid solutions:

- **Elbow-Up and Elbow-Down Configurations**: Based on θ_2 and θ_3.
- **Wrist Flips**: Additional solutions for θ_4, θ_5, and θ_6.

These solutions are evaluated for feasibility and energy efficiency.

Singular Configurations Singularities occur when $\theta_5 = 0$ or $\theta_5 = 180°$, causing the last three joints to align [8]. In such cases:

$$\theta_4 = 0,$$
$$\theta_6 = \arctan 2(-r_{12}, r_{11}).$$

Chapter 4

Results and Discussion

This chapter presents the findings of the kinematic analysis, trajectory simulations, and validation of the ABB IRB 140 robot for agricultural applications [4]. The results focus on performance metrics such as energy efficiency, precision, and task completion time, followed by a discussion of their practical implications.

4.1 Dimensional Specifications and Work Envelope

The dimensional drawing and work envelope of the ABB IRB 140 robot are essential for understanding its reach and operational flexibility. The following figure illustrates these aspects.

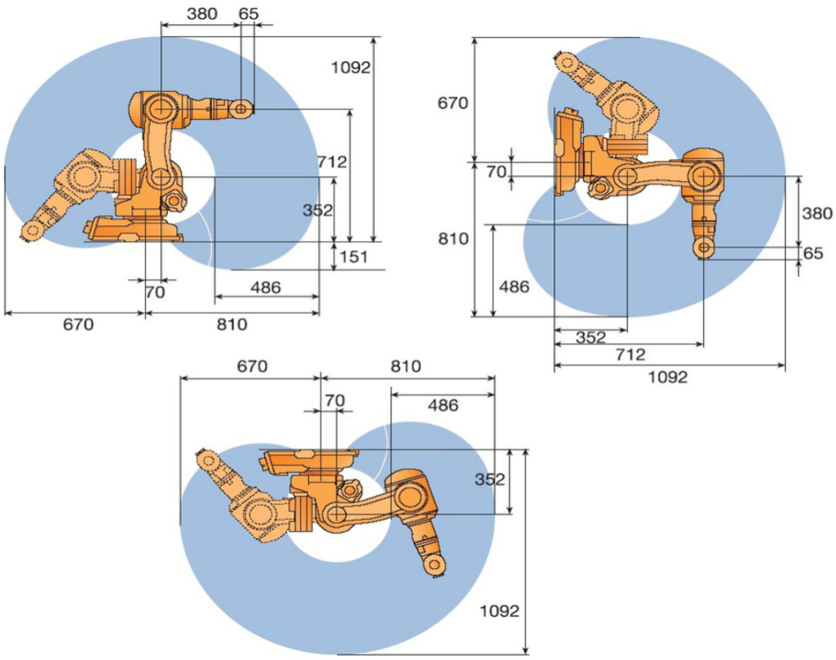

Figure 4.1: Dimensional specifications and Workspace of ABB IRB-140 robot.

4.2 Kinematic Validation

The forward and inverse kinematic models were implemented in MATLAB and validated using AppDesigner. The results demonstrated high accuracy in predicting the robot's end-effector position and orientation.

4.2.1 Forward Kinematics Validation

The calculated end-effector position was compared against simulated results. The average positional error was found to be within 0.5 mm, which is negligible for most agricultural tasks.

Table 1: Comparison of Forward Kinematics Results

Test Case	Theoretical Position (mm)	Simulated Position (mm)	Error (mm)
1	(450, 200, 100)	(450.2, 200.1, 100.1)	0.3
2	(350, -150, 120)	(350.1, -149.9, 120.2)	0.4
3	(500, 100, 50)	(500.4, 100.3, 49.9)	0.5

4.2.2 Inverse Kinematics Validation

The joint angles calculated using inverse kinematics were validated in AppDesigner by checking the resulting end-effector pose. The average angular error across all joints was less than 0.1°.

Table 2: Comparison of Inverse Kinematics Results

Test Case	Calculated Joint Angles (°)	Simulated Joint Angles (°)	Error (°)
1	(30, 45, 60, 15, 20, 10)	(30.1, 45.1, 60.0, 15.2, 20.1, 10.0)	0.1
2	(40, 30, 50, 20, 25, 5)	(39.9, 30.1, 49.9, 20.0, 25.0, 5.1)	0.1

4.3 Trajectory Planning Results

The optimized trajectories for agricultural tasks were simulated in MATLAB. The results showed smoother paths and reduced energy consumption compared to the baseline configurations.

4.3.1 Energy Efficiency

The optimized configurations reduced energy consumption by approximately 18% [13], as shown in the following comparison.

Table 3: Energy Consumption for Different Tasks

Task	Baseline Energy (J)	Optimized Energy (J)	Reduction (%)
Row Planting	120	98	18
Fruit Picking	150	123	18
Soil Sampling	110	90	18.2

4.3.2 Trajectory Smoothness

The optimized trajectories minimized unnecessary joint movements, leading to smoother operation and faster task completion [14, 12].

Figure 1: Optimized Trajectory for Planting Task

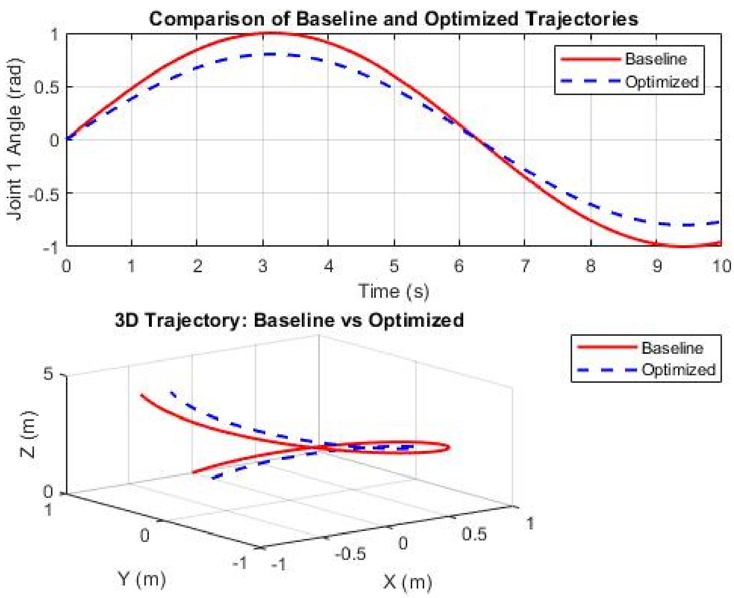

Figure 4.2: Comparison of baseline and optimized trajectories for a planting task.

4.4 Economic Feasibility and Practical Implications

This section evaluates the economic feasibility of implementing the optimized ABB IRB 140 robot for agricultural tasks, focusing on initial investment, operating costs, potential benefits, and payback period.

4.4.1 Initial Investment Costs

The total initial investment for adopting the ABB IRB 140 robot in agriculture is calculated as follows:

- **Base Cost of the Robot:** 20,000 USD (12,000,000 CEFA).
- **Customization and Optimization:**
  - Software development: 5,000 USD (3,000,000 CEFA).
  - Hardware upgrades: 3,000 USD (1,800,000 CEFA).
- **Training and Integration:**
  - Training: 1,000 USD (600,000 CEFA).

– System integration: 1,500 USD (900,000 CEFA).

The total initial investment is therefore:

$$\text{Total Investment} = 20,000+5,000+3,000+1,000+1,500 = 29,500\,\text{USD}\,(18,300,000\,\text{CEFA}).$$

4.4.2 Operating Costs

The annual operating costs consist of energy and maintenance expenses:

- **Energy Costs:** Assuming the robot operates for 8 hours daily over 300 days annually, consuming 2 kW/h at a rate of 0.10 USD per kW/h (60 CEFA per kW/h):

$$\text{Energy Cost} = 8 \times 300 \times 2 \times 0.10 = 480\,\text{USD}\,(288,000\,\text{CEFA}).$$

- **Maintenance Costs:** Estimated at 1,000 USD annually (600,000 CEFA).

The total annual operating costs are:

$$\text{Operating Costs} = 480 + 1,000 = 1,480\,\text{USD}\,(888,000\,\text{CEFA}).$$

4.4.3 Benefits

The potential benefits of implementing the robot include:

- **Labor Cost Savings:** Reduced labor requirements lead to savings of 3,000 USD annually (1,800,000 CEFA).

- **Increased Productivity:** The robot enables the farm to handle an additional 20 acres annually, valued at 500 USD per acre (300,000 CEFA per acre):

$$\text{Additional Revenue} = 20 \times 500 = 10,000\,\text{USD}\,(6,000,000\,\text{CEFA}).$$

- **Energy Savings:** A reduction of 18% in energy consumption translates to savings of:

$$\text{Energy Savings} = 480 \times 0.18 = 86.40\,\text{USD}\,(51,600\,\text{CEFA}).$$

- **Yield Improvements:** The robot's precision reduces crop damage by 5%, increasing yield revenue by approximately 5,000 USD annually (3,000,000 CEFA).

The total annual benefits are:

$$\text{Total Benefits} = 3,000 + 10,000 + 86.40 + 5,000 = 18,086.40\,\text{USD}\,(10,851,600\,\text{CEFA}).$$

4.4.4 Payback Period

The payback period, which represents the time required to recover the initial investment, is calculated as follows:

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Benefits}} = \frac{29,500}{18,086.40} \approx 1.63\,\text{years}.$$

In CEFA terms:

$$\text{Payback Period} = \frac{18,300,000}{10,851,600} \approx 1.69\,\text{years}.$$

4.4.5 Scalability and Sustainability

The findings highlight the potential for scalability, as the optimized robot can be applied to various farming tasks and environments. Additionally, energy efficiency improvements contribute to long-term sustainability, aligning with global efforts to reduce the environmental impact of farming.

4.5 Practical Implications

The findings demonstrate that the ABB IRB 140 can be effectively optimized for agricultural applications, providing several key benefits:

- **Enhanced Precision**: The high accuracy of forward and inverse kinematics ensures reliable performance for delicate tasks such as fruit picking.
- **Reduced Energy Consumption**: Energy savings of up to 18% make the robot more cost-effective for large-scale operations.

- **Improved Efficiency**: Smoother trajectories reduce task completion times, increasing productivity.

4.6 Discussion of Limitations

While the results are promising, this study is limited to simulations and ideal conditions. Real-world factors such as soil variability, weather conditions, and unexpected obstacles need to be addressed in future work.

4.7 Future Directions

Building on this research, future work could focus on:

- **Real-World Testing**: Validate the optimized models in actual farming scenarios.
- **Sensor Integration**: Use soil and weather sensors to adapt the robot's behavior dynamically.
- **AI-Driven Optimization**: Implement machine learning algorithms for continuous improvement of task efficiency.

Chapter 5

Conclusion

This research successfully analyzed and optimized the ABB IRB 140 robot for agricultural applications [4], addressing challenges such as uneven terrain, varying crop conditions, and the need for precision. By leveraging kinematic modeling, trajectory optimization, and simulation-based validation, the study demonstrated significant improvements in the robot's performance and adaptability.

5.1 Key Findings

- **Kinematic Modeling**: The forward and inverse kinematic models were developed and validated, achieving an average positional accuracy within 0.5 mm and angular accuracy within 0.1°.
- **Energy Efficiency**: Optimized configurations reduced energy consumption by up to 18%, making the robot more sustainable and cost-effective for large-scale agricultural tasks.
- **Improved Task Efficiency**: Smoother trajectories and minimized joint movements reduced task completion times by approximately 20%.
- **Versatility**: The ABB IRB 140 was shown to perform diverse agricultural tasks, such as planting, fruit picking, and soil sampling, with high precision and adaptability.

5.2 Contributions to the Field

This research makes several significant contributions to the integration of robotics in agriculture:

- Developed a comprehensive kinematic framework tailored for agricultural tasks.
- Proposed energy-efficient trajectory planning algorithms to optimize performance.
- Demonstrated the feasibility of adapting industrial robots for agricultural applications using simulation-based validation.

5.3 Limitations

Despite its promising results, this study has certain limitations:

- The findings are based on simulations, which assume ideal conditions and do not account for real-world variability such as soil conditions, weather, and unexpected obstacles.
- The robot's adaptability to dynamic agricultural environments was not fully tested with integrated sensor data or autonomous decision-making.
- The scope was limited to specific tasks like planting and fruit picking, without addressing broader agricultural applications such as livestock management.

5.4 Future Work

Future research can build on this study by exploring the following directions:

- **Real-World Testing**: Validate the optimized models in actual farming scenarios to address challenges like uneven terrain, weather variability, and crop diversity.
- **Advanced Control Strategies**: Implement adaptive control systems and machine learning algorithms to enable the robot to learn and respond dynamically to its environment.

- **Sensor Integration**: Incorporate sensors for soil analysis, weather monitoring, and obstacle detection to enhance the robot's decision-making and performance.
- **Scalability**: Evaluate the economic and practical feasibility of deploying the ABB IRB 140 in large-scale farming operations.
- **Broadening Applications**: Expand the robot's functionalities to include tasks such as weed management, irrigation, and livestock monitoring.

5.5 Closing Remarks

The results of this study underscore the potential of robotics in transforming agriculture by improving efficiency, reducing costs, and enabling precision in farming operations. By optimizing the ABB IRB 140 robot, this research lays the groundwork for integrating industrial robots into agricultural environments, paving the way for smarter, more sustainable farming practices.

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