# Simulation and Experimental Evaluation of a Robotic Handling Arm for Operational Optimization in Cold-Chain Industries

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**Abstract -** *This study explores the development of a semi-automated robotic arm designed to address inefficiencies observed in frozen food industries where manual pick-and-place tasks dominate operations. These repetitive tasks contribute to early fatigue and inconsistency in worker performance, particularly during the initial hours of shifts. To tackle this issue, a simulation-centric robotic model was created using MATLAB and Simulink, leveraging the Simscape Multibody Toolbox to replicate the mechanical behavior of a manipulator. The simulated environment facilitated precise analysis of motion dynamics, actuator control, and trajectory optimization. Complementing the simulation, a physical prototype—constructed as a non-integrated black-box model using Arduino Nano—validates the basic control mechanism through joystick inputs and servo motion. While not a fully realized Digital Twin, the system enables experimentation with its core principles, establishing the groundwork for real-time predictive modeling and performance tuning. The projected outcome would indicate improved handling stability and productivity, demonstrating the potential of simulation-augmented automation in enhancing cold storage operational efficiency.*

***Key Words***: Manipulator, simulation, Arduino nano, kinematics, cold chain automation, prototyping, productivity, trajectory control.

## 1.INTRODUCTION

In frozen food processing units, maintaining consistent performance in sub-zero environments poses challenges due to worker fatigue and reduced dexterity during repetitive tasks. These inefficiencies lower throughput and increase the risk of human error, highlighting the need for automation. This study addresses these issues by developing a robotic arm for automated pick-and-place operations. A MATLAB-Simulink simulation models kinematics and control logic, while a microcontroller-based black-box prototype validates physical feasibility. The combined virtual and physical approaches support scalable automation in cold storage settings.

## 2. LITERATURE REVIEW

Recent advancements in industrial automation highlight the growing relevance of robotic arms in enhancing operational efficiency, precision, and safety. Various studies emphasize the role of simulation and prototyping in optimizing robotic systems for specialized tasks.

One body of research focuses on simulation-based modelling using tools such as MATLAB and Simulink. A 3-DOF robotic manipulator was modelled using computed torque control (CTC) to ensure accurate trajectory tracking, showcasing the significance of dynamic modelling in control optimization. Another study employed the Denavit-Hartenberg convention for kinematic analysis, integrating MATLAB simulations with Arduino-driven actuators for effective joint coordination and motion control. The use of inverse kinematics further validated motion accuracy and system reliability.

Prototyping efforts have demonstrated practical feasibility through microcontroller-based systems. Lightweight pick-and-place robotic arms utilizing servo motors, Arduino platforms, and joystick inputs were shown to deliver accurate object manipulation. Some implementations incorporated pneumatic circuits and revolute joints to handle larger payloads or reduce operational cycle time, with applications in palletizing, sorting, and automotive assembly.

In domain-specific contexts such as the food industry, robotic automation has contributed to productivity gains, improved hygiene, and reduced manual effort. Technologies like SCARA robots and vision-assisted mechanisms have been deployed in packaging and processing, although high initial costs remain a challenge.

Colour-sorting robotic systems have also been explored, where robotic arms use sensor input to classify and sort objects, indicating strong potential in laboratory automation and quality control scenarios.

Collectively, these studies underscore the importance of combining simulation environments with physical prototyping to create efficient, adaptable, and application-specific robotic systems.

## 3. RESEARCH PROBLEM AND DATA COLLECTION

Manual pick-and-place operations in cold storage facilities are inefficient, error-prone, and time-consuming. These operations are hindered by labor costs, low throughput, and the challenges of working in sub-zero temperatures. This research addresses the need for an affordable, efficient automation solution to improve operational efficiency in such environments. Data was collected for the manual pick-and-place processes to quantify improvements. The table below summarizes key operational and workforce metrics observed:

**Workstation Details:**
6 workers each station | 8-hour shift
**Expected Productivity:** 10–13 kg/worker/hrs
**Expected Daily Output:** 650–750 kg
Analyzed data:

| WORKERS | WORKING HOURS | | | | | | | | TOTAL (KG) |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| 1 | 13 | 12 | 11 | 10 | 9 | 8 | 8 | 7 | 78 |
| 2 | 12 | 13 | 12 | 11 | 10 | 9 | 8 | 5 | 80 |
| 3 | 14 | 13 | 12 | 11 | 10 | 9 | 7 | 7 | 83 |
| 4 | 11 | 10 | 9 | 9 | 8 | 7 | 8 | 7 | 69 |
| 5 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 68 |
| 6 | 15 | 14 | 13 | 12 | 10 | 9 | 6 | 7 | 86 |
| Total(Kg) | 77 | 73 | 67 | 62 | 55 | 49 | 43 | 38 | 464 |

Table 1: Collected Data

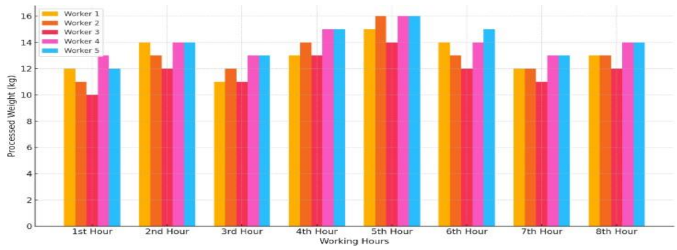
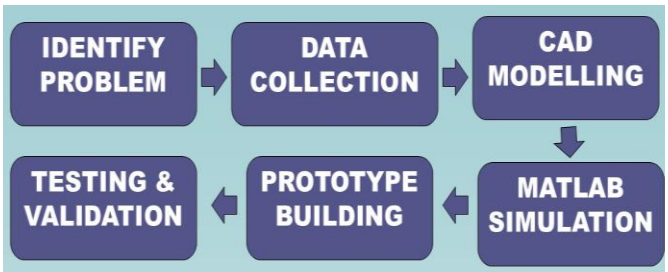



Figure 1: Graphical presentation of weight vs hours

It was observed from the data collected that workers perform best in the initial hours of their shifts, with productivity dropping over time due to fatigue. Some individuals showed sharper declines, suggesting possible ergonomic issues or skill gaps which can lead to face bottleneck situations and delay in supplying goods.

## 4. METHODOLOGY




## 5. CAD MODEL

The CAD model was built using onshape application before importing it on the MATLAB for simulation where various suitable toolboxes were used to make it work observe the virtual movements before building it in real time.

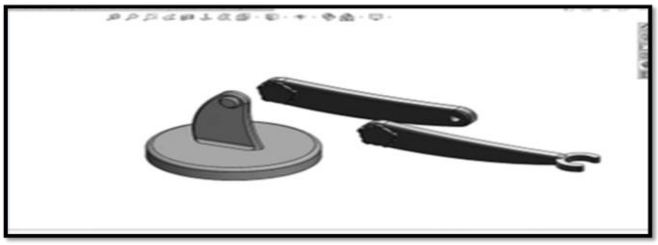


Figure 2: Before assembling

Figure 3: Final model

## 6. MATLAB IMPLEMENTATION

A arm was modeled using CAD and simulated in MATLAB-Simulink with Simscape Multibody to analyze motion dynamics and control accuracy. Key parameters such as torque, speed, and joint angles were evaluated using PID control. Though not a full Digital Twin, the approach supports core simulation-to-prototype verification.

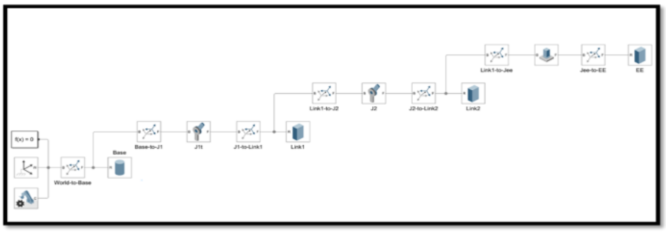


Figure 4: Simulink blocks for simulation

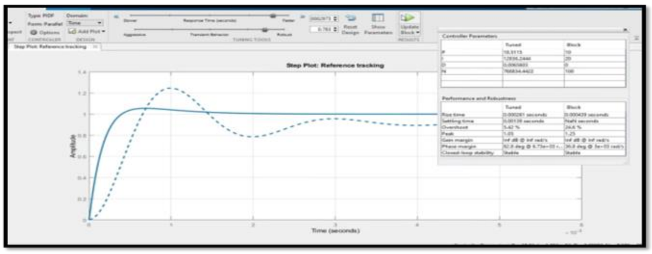


Figure 5: Amplitude V/S Time

## 7. PROTOTYPE BUILDING

The prototype showcases a functional simplified robotic arm controlled via Arduino nano and servo motors. Designed as a black-box model, demonstrates the core pick and place through joysticks type components, offering a tangible preview of the simulated system and validating real-world feasibility.

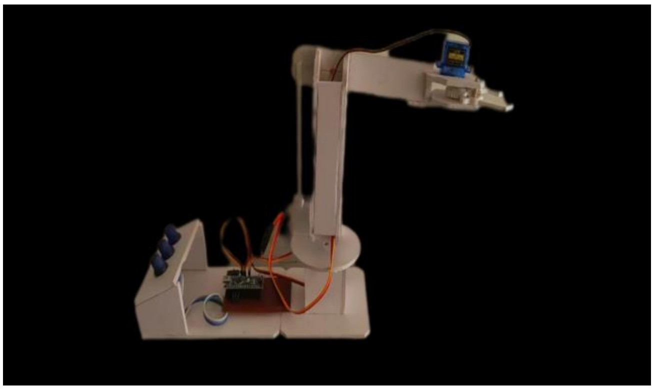


Figure 6: Black box model (Prototype)

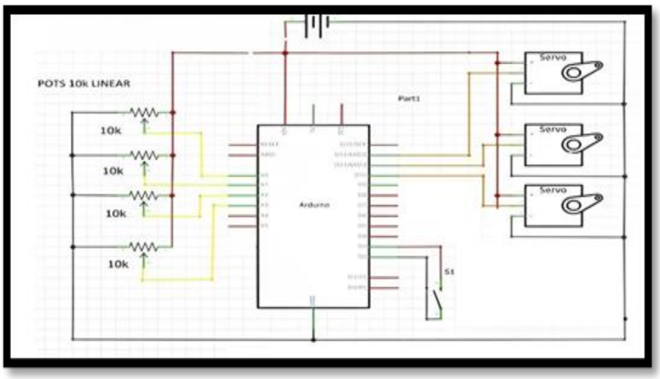
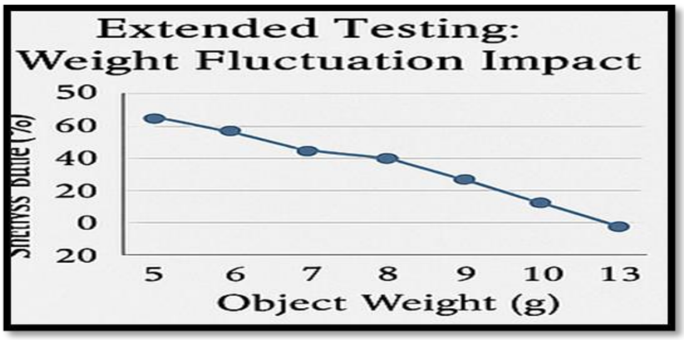



Figure 7: Circuit diagram

## 8. TESTING AND RESULTS

Preliminary testing reveals that the robotic arm has limited payload capacity and exhibits reduced consistency in performance. This is primarily due to the use of PVC material, which, despite being lightweight and economical, lacks the structural strength required for stable and precise operations.



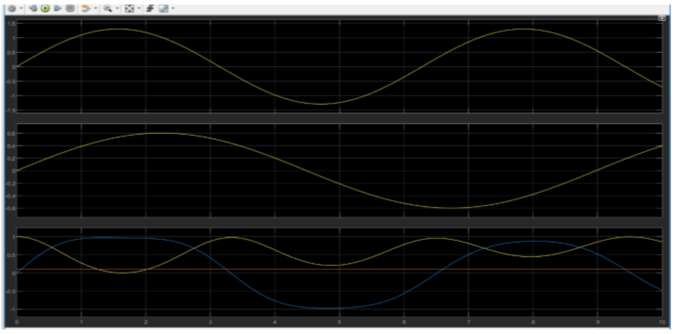



Figure 8: Simulink results

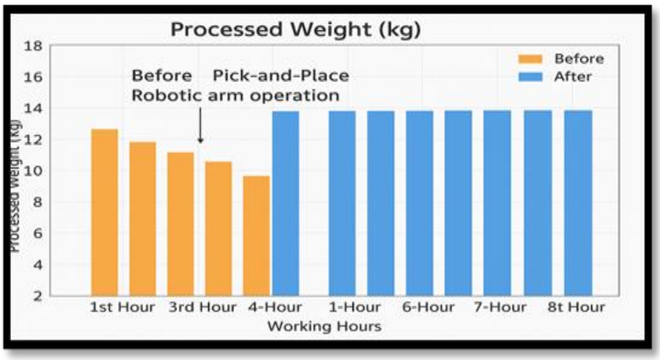



Figure 9: Projected Improvement

## 9. CONCLUSIONS

This project presents a simulation-driven robotic arm alongside a functional black-box prototype, developed to address labor-related challenges in frozen storage environments. Although initial testing indicates limitations in payload handling, the system effectively demonstrates conceptual feasibility. The overall framework provides a solid foundation for future enhancements, including the integration of sensors and increased load capacity, paving the way for scalable automation solutions in cold-chain industries

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