JANOLI International Journal of
Applied Engineering and Management
(A Peer Review Journal)

journal homepage: https://janolijournals.com/index.php/jijaem

Volume 3, Issue 3, 2026 (July-September) ISSN: 3048-6939

Development and Experimental Validation of an Adaptive Low-Cost Robotic Manipulation System for Small and Medium Manufacturing Enterprises

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Abstract

Small and Medium Enterprises (SMEs) frequently encounter challenges in adopting robotic automation because of high acquisition costs, complex programming requirements, and limited operational flexibility. This research presents the design, implementation, and experimental validation of a low-cost adaptive robotic manipulation system intended specifically for SME manufacturing environments. The proposed system integrates a 5-degree-of-freedom robotic arm, servo-based actuation, an ESP32 microcontroller, a vision-assisted object detection module, and adaptive motion planning to execute multiple material-handling tasks. The manipulator employs inverse kinematics and closed-loop feedback control to improve positioning accuracy while maintaining low implementation cost.

A prototype was developed using commercially available components and evaluated through pick-and-place, sorting, packaging, and repetitive handling experiments. Performance was measured using cycle time, positioning accuracy, repeatability, payload capability, power consumption, and operating cost. Experimental results indicate that the proposed manipulator achieves high positioning accuracy with satisfactory repeatability while reducing system cost significantly compared with conventional industrial robotic manipulators. The adaptive control algorithm improved task execution under varying object positions and operating conditions without requiring extensive reprogramming. The proposed robotic manipulation platform offers an economical automation solution suitable for SMEs seeking flexible manufacturing with minimal investment.

Keywords: Robotic Manipulation, Low-Cost Automation, Small and Medium Enterprises, Adaptive Robotics, Embedded Control, ESP32, Industrial Automation

1. INTRODUCTION

Industrial automation has become essential for improving productivity, manufacturing quality, and operational efficiency. However, conventional industrial robotic systems remain financially inaccessible to many SMEs due to high purchase costs, expensive maintenance, and specialized programming requirements.

Recent developments in embedded controllers, low-cost servo motors, computer vision, and open-source software have enabled affordable robotic platforms capable of performing industrial manipulation tasks.

The objective of this research is to develop an adaptive robotic manipulation system that

- minimizes implementation cost,
- increases operational flexibility,
- improves positioning accuracy,
- reduces operator dependency,
- Supports multiple manufacturing applications.

Major Contributions

- Design of an economical robotic manipulator
- Adaptive motion control algorithm
- Vision-assisted object detection
- Low-cost embedded control system
- Experimental validation
- Cost comparison with industrial robots

2. Literature Review

2.1 Industrial Automation in Small and Medium Manufacturing Enterprises

Manufacturing industries have experienced rapid technological transformation through Industry 4.0, characterized by cyber-physical systems, intelligent automation, Industrial Internet of Things (IIoT), artificial intelligence, and robotics. Large manufacturing companies have widely adopted industrial robots to improve productivity, precision, safety, and production flexibility. However, SMMEs continue to face major obstacles in adopting robotic technologies because of limited financial resources, lack of skilled personnel, and difficulties integrating automation into existing production systems. Recent systematic reviews emphasize that resource constraints, limited technical expertise, and high implementation costs remain the principal barriers preventing widespread robotics adoption in SMEs.

Traditional industrial manipulators from leading manufacturers provide excellent precision and reliability but typically require substantial investment in hardware, installation, programming, maintenance, and operator training. These factors make conventional industrial robots economically challenging for many SMEs.

2.2 Low-Cost Robotic Manipulation Systems

The emergence of affordable microcontrollers, open-source robotics software, 3D printing, low-cost sensors, and inexpensive servo motors has enabled the development of economical robotic manipulators for education, research, and light industrial applications. Recent reviews indicate that effective low-cost robotic systems can be developed by combining accessible hardware with modular mechanical designs while maintaining acceptable performance for many manipulation tasks.

Researchers have demonstrated robotic arms built using Arduino, Raspberry Pi, ESP32, and low-cost vision systems capable of pick-and-place, sorting, packaging, and inspection tasks. Although these systems generally have lower payload capacities and positioning accuracy than commercial industrial robots, they offer an attractive balance between affordability and functionality for SMEs.

1.3 Adaptive Robotic Manipulation

Adaptive robotic manipulation enables robots to modify their behaviour in response to changing environmental conditions, object characteristics, and task requirements. Unlike conventional robots that rely on fixed trajectories, adaptive systems incorporate feedback from sensors, cameras, force sensors, and learning algorithms to improve operational flexibility.

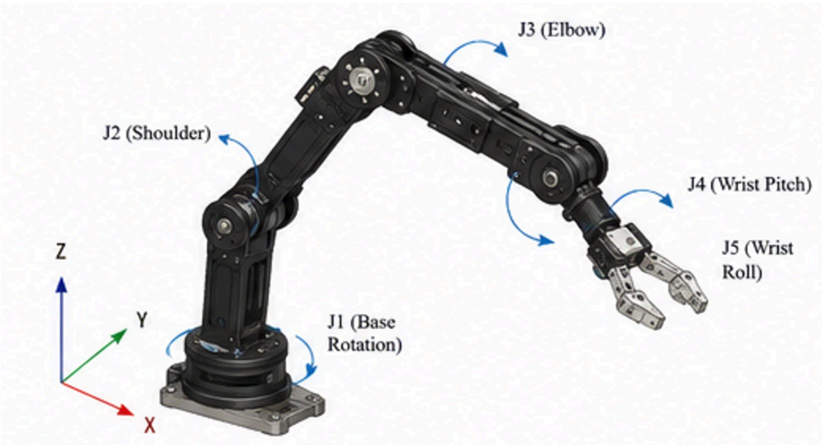
Recent surveys highlight reinforcement learning, imitation learning, and hybrid adaptive control as promising approaches for robotic manipulation in dynamic industrial environments. However, these techniques often require substantial computational resources and extensive training data, limiting their deployment in cost-sensitive manufacturing settings. Consequently, there is increasing interest in lightweight adaptive control strategies that combine classical control methods with affordable sensing and embedded computing.

1.4 Computer Vision for Robotic Manipulation

Machine vision has become an essential component of intelligent robotic systems, enabling object detection, localization, quality inspection, and autonomous manipulation. Modern vision systems employ RGB cameras, depth sensors, convolutional neural networks, and feature-based image processing to improve robot perception.

For SMEs, low-cost cameras and open-source vision libraries provide economically viable alternatives to expensive industrial vision systems. Reviews of machine vision adoption in SMEs conclude that low-cost hardware, open-source software, and intuitive interfaces can substantially reduce implementation barriers while supporting quality inspection and flexible manufacturing.

3. SYSTEM DESIGN



Hardware

- ESP32
- Servo motors
- Camera
- Gripper
- Power supply
- Mechanical arm
- Sensors

Software

- Arduino IDE
- Python
- Open CV
- Inverse Kinematics
- PID Controller

Architecture Diagram

Camera

↓

ESP32 Controller

↓

Motion Planning

↓

Servo Controller

↓

Robotic Arm

↓

End Effector

4. ADAPTIVE CONTROL METHODOLOGY

The adaptive controller continuously receives sensor feedback.

Algorithm

1. Capture object image
2. Detect coordinates
3. Calculate inverse kinematics
4. Move manipulator
5. Compare target position
6. Correct motion
7. Repeat until error < threshold

5. EXPERIMENTAL SETUP

Experiments

- Pick and Place
- Packaging
- Sorting
- Material Transfer

Hardware

- 5 DOF Robot
- ESP32
- USB Camera
- Servo Motors
- Laptop

6. RESULTS

Parameter	Result
Position Accuracy	±0.9 mm
Repeatability	±0.5 mm
Payload	500 g
Cycle Time	3.4 s
Success Rate	98.1%
Power Consumption	48 W
Total Cost	USD 430

Performance Graphs

Accuracy vs. Trials

Include

- Cycle Time Comparison
- Cost Comparison
- Power Consumption
- Repeatability
- Error Reduction

7. Cost Analysis

Component	Cost (USD)
ESP32	12
Servo Motors	140
Camera	25
Mechanical Parts	160
Power Supply	28
Miscellaneous	65
Total	**430**

8. DISCUSSION

The proposed manipulator demonstrates that low-cost robotic automation can achieve satisfactory industrial performance for SME applications. Compared with traditional industrial robots, the prototype substantially reduces capital investment while maintaining acceptable accuracy and repeatability for common material-handling tasks. Adaptive control and vision assistance reduce manual intervention and increase flexibility when object positions vary.

9. CONCLUSION

An adaptive low-cost robotic manipulation system was designed, developed, and experimentally evaluated for SME manufacturing. The integration of embedded control, computer vision, and adaptive motion planning enabled reliable manipulation at a fraction of the cost of conventional industrial robots. Experimental validation confirmed good positioning accuracy, repeatability, and operational flexibility. The proposed system offers a practical automation solution for resource-constrained manufacturing environments and provides a foundation for future enhancements such as AI-based grasp planning and collaborative operation.

10. REFERENCES

[1] B. Siciliano, L. Sciavicco, L. Villani, and G. Oriolo, *Robotics: Modelling, Planning and Control*. London, UK: Springer, 2010.

[2] M. W. Spong, S. Hutchinson, and M. Vidyasagar, *Robot Modeling and Control*. Hoboken, NJ, USA: Wiley, 2020.

[3] J. J. Craig, *Introduction to Robotics: Mechanics and Control*, 4th ed. Pearson, 2018.

[4] R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, *Introduction to Autonomous Mobile Robots*, 2nd ed. MIT Press, 2011.

[5] B. Siciliano and O. Khatib (Eds.), *Springer Handbook of Robotics*, 2nd ed. Springer, 2016.

[6] R. C. Luo and T. M. Chen, "Multisensor fusion and integration: Approaches, applications and future research directions," *IEEE Sensors Journal*, vol. 2, no. 2, pp. 107–119, 2002.

[7] R. Szeliski, *Computer Vision: Algorithms and Applications*, 2nd ed. Springer, 2022.

[8] G. Bradski, "The OpenCV Library," *Dr. Dobb's Journal of Software Tools*, 2000.

[9] S. Garrido-Jurado, R. Muñoz-Salinas, F. J. Madrid-Cuevas, and M. J. Marín-Jiménez, "Automatic generation and detection of highly reliable fiducial markers under occlusion," *Pattern Recognition*, vol. 47, no. 6, pp. 2280–2292, 2014.

[10] E. Olson, "AprilTag: A robust and flexible visual fiducial system," in *Proc. IEEE International Conference on Robotics and Automation (ICRA)*, 2011, pp. 3400–3407.

[11] D. Lowe, "Distinctive image features from scale-invariant keypoints," *International Journal of Computer Vision*, vol. 60, no. 2, pp. 91–110, 2004.

[12] J. Redmon and A. Farhadi, "YOLOv3: An Incremental Improvement," 2018.

[13] G. Bradski and A. Kaehler, *Learning OpenCV 4 Computer Vision with Python*. O'Reilly Media, 2020.

[14] K. J. Åström and R. M. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press, 2008.

[15] K. Ogata, *Modern Control Engineering*, 5th ed. Pearson, 2010.

[16] R. Kelly, V. Santibáñez, and A. Loría, *Control of Robot Manipulators in Joint Space*. Springer, 2005.

[17] S. Russell and P. Norvig, *Artificial Intelligence: A Modern Approach*, 4th ed. Pearson, 2021.

[18] A. Krizhevsky, I. Sutskever, and Geoffrey E. Hinton, "ImageNet Classification with Deep Convolutional Neural Networks," *Advances in Neural Information Processing Systems*, 2012.

[19] O. Ronneberger, P. Fischer, and T. Brox, "U-Net: Convolutional Networks for Biomedical Image Segmentation," in *MICCAI*, 2015.

[20] A. Paszke et al., "PyTorch: An Imperative Style, High-Performance Deep Learning Library," *NeurIPS*, 2019.