Design and Development of 3D Printed Scara Robotic Arm

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ABSTRACT - This paper focuses on the design and development of a 3D printed SCARA robotic arm using additive manufacturing to achieve low cost, lightweight, and customizable robotic solutions. The arm components were modelled in CAD and fabricated using FDM 3D printing, reducing material waste and enabling rapid prototyping. Stepper motors, servo motors, and an Arduino-based control system were integrated for precise movement and operation. The robotic arm was assembled, calibrated, and tested to perform pick-and-place and linear/radial motions. The system demonstrates potential for educational, research, and light industrial applications, while also providing scope for future improvements in payload and automation.

1. INTRODUCTION

The rapid advancement of industrial automation has significantly increased the demand for robotic manipulators capable of performing high-speed, high-precision, and repetitive tasks with minimal human intervention. Among various robotic architectures, the Selective Compliance Assembly Robot Arm (SCARA) has emerged as a preferred solution for applications such as pick-and-place operations, electronic assembly, packaging, and light material handling due to its inherent structural rigidity in the vertical direction and selective compliance in the horizontal plane. These characteristics enable SCARA robots to achieve high positioning accuracy, fast cycle times, and reliable repeatability, making them well-suited for planar motion-dominant tasks in manufacturing environments.

Despite their advantages, conventional SCARA robotic systems remain economically inaccessible for small-scale industries, academic laboratories, and research institutions because of high manufacturing costs, complex machining requirements, and proprietary control architectures. The dependency on precision-machined metallic components and industrial-grade controllers further increases the overall system cost, limiting the adoption of robotic automation in cost-sensitive sectors. Consequently, there is a growing research interest in developing low-cost, modular, and easily manufacturable robotic platforms without significantly compromising functional performance.

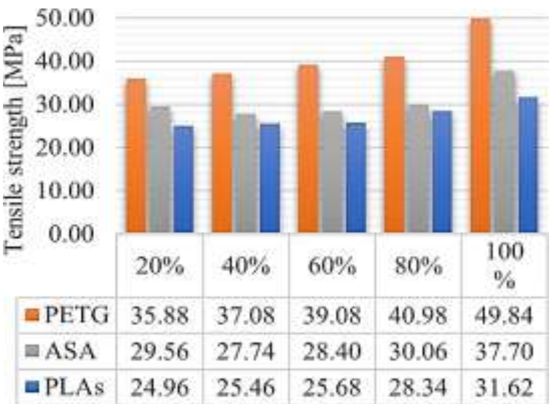
Additive manufacturing, particularly Fused Deposition Modelling (FDM), has gained prominence as a viable alternative to traditional subtractive manufacturing for robotic structures. The ability to fabricate complex geometries, reduce material waste, and enable rapid prototyping makes FDM especially attractive for robotic arm development. Thermoplastic materials such as PETG offer a favorable balance between mechanical strength, dimensional stability, and printability, enabling the fabrication of lightweight yet structurally reliable robotic components. The integration of 3D printing with open-source electronics and embedded control platforms further enhances design flexibility and system scalability.

2. RESEARCH METHODOLOGY

The methodology adopted in this work focuses on the systematic development and evaluation of a low-cost SCARA robotic arm using additive manufacturing and embedded control. A SCARA configuration was selected based on workspace efficiency and suitability for planar pick-and-place operations. The mechanical structure was designed using CAD tools, and kinematic feasibility was verified through forward and inverse kinematic relationships

Fig 1.SCARA Robotic Arm

Structural components were fabricated using Fused Deposition Modelling with PETG material, selected for its balance of mechanical strength, printability, and dimensional stability. Actuation was achieved using



stepper motors for joint motion and a servo motor for end-effector control, driven by an Arduino-based embedded controller. Basic motion coordination, homing, and limit enforcement were implemented to ensure safe and repeatable operation.

3. MATERIAL SELECTION:

The selection of PETG as the structural material for the 3D printed SCARA robotic arm was based on a comparative mechanical performance analysis with commonly used FDM materials, namely ASA and PLA-Strongman. Since robotic arm components are subjected to cyclic loading, joint-level stress concentration, and moderate thermal exposure during continuous operation, the selected material must exhibit a favorable balance of tensile strength, yield strength, elastic modulus, and deformation capability.

3.1 Comparative Mechanical Property Evaluation

Table 1 summarizes the average tensile mechanical properties at 100% infill density, directly adopted from the experimental results reported in the reference journal.

Infill density	*Rm*	*Ry*	*Rb*	*E*	*ε*
PETG					
20%	35.88	27.86	28.53	1.56	3.52
40%	37.08	26.64	26.56	1.72	4.08
60%	39.08	30.86	29.53	1.72	3.74
80%	40.98	31.16	33.11	1.86	3.3
100%	49.84	38.8	25.13	2.1	6.88

The results indicate that PETG exhibits the highest tensile strength and yield strength among the evaluated materials. Compared to ASA, PETG shows an increase of approximately 32% in tensile strength, while the improvement reaches 57% when compared with PLA-Strongman. Similarly, the yield strength of PETG is 23% higher than ASA and 46% higher than PLA-Strongman, which is critical for load-bearing robotic joints where elastic deformation must be avoided

3.2 Graph-Based Trend Analysis (Strength vs Infill Density)

The tensile strength variation with infill density, as illustrated in the reference graphs, demonstrates a nearly linear increase in strength for PETG as infill density increases from 20% Fig 2.Tensile Strength
to 100%. For PETG, tensile strength increases from 35.88 MPa at 20% infill to 49.84 MPa at 100% infill, representing an improvement of approximately 39%

Material	Tensile Strength Rm (MPa)	Yield Strength Ry (MPa)	Elastic Modulus E (GPa)
PETG	37.08	26.64	1.72
ASA	27.74	23.9	1.5
PLA	25.46	22.58	1.7

In contrast, ASA and PLA-Strongman exhibit lower absolute strength values across all infill densities. Although all materials show strength improvement with increased infill, PETG consistently remains superior, confirming its suitability for structural robotic components where stiffness and strength must coexist.

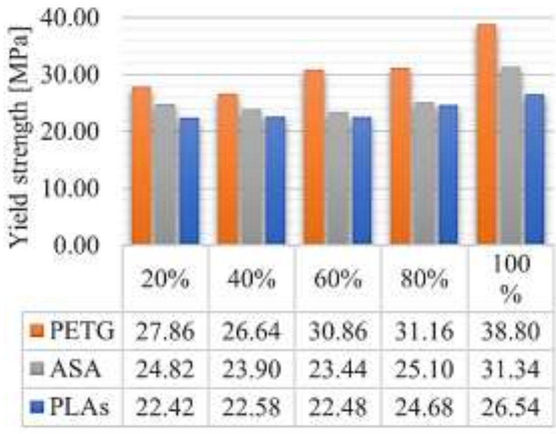


Fig 3.Yield Strength

4.SYSTEM DESIGN AND ARCHITECTURE:

Mechanical Design and CAD Framework

The mechanical architecture of the proposed SCARA robot was developed with emphasis on planar kinematic efficiency, structural stiffness, and reduced inertial loading. Link lengths and joint placements were optimized through CAD-based spatial analysis to maximize reachable workspace while minimizing torque demand on the actuators. Bearing-supported revolute joints were incorporated to reduce frictional losses and backlash, directly influencing positional repeatability. The CAD model was further utilized to validate assembly tolerances, joint alignment, and collision-free motion across the operational envelope, ensuring mechanical feasibility prior to fabrication.

Fig.4.CAD Design

5. ANALYSIS:

1. **Pulley Ratio Selection (Joint-Wise)**

Joint	Driver Pulley (Teeth)	Driven Pulley (Teeth)	Reduction Ratio (i)
Joint-1 (Base)	16	320	20:01
Joint-2 (Elbow)	16	256	16:01
Joint-3 (Z-axis)	20	80	04:01

Base Joint Gear Ratio

$i_1 = N/n = 320 / 16$

$i_1 = 20$

$i_1 = 20 : 1$

2. **Torque Output:**

i) Elbow Joint (16:1 Reduction):

$\tau_m = 0.45$ N·m

$\eta = 0.92$

$\tau_{out,1} = \tau_m \times i_1 \times \eta$

$\tau_{out,1} = 0.45 \times 20 \times 0.92$

$\tau_{out,1} = 9.0 \times 0.92$

$\tau_{out,1} = 8.28$ N·m

ii) Elbow Joint (16:1 Reduction):

$i_2 = 16$

$\tau_{out,2} = \tau_m \times i_2 \times \eta$

$\tau_{out,2} = 0.45 \times 16 \times 0.92$

$\tau_{out,2} = 7.2 \times 0.92$

$\tau_{out,2} = 6.62$ N·m

iii) Vertical (Z-Axis) Joint (4:1 Reduction):

$i_3 = 4$

$\tau_{out,3} = \tau_m \times i_3 \times \eta$

$\tau_{out,3} = 0.45 \times 4 \times 0.92$

$\tau_{out,3} = 1.8 \times 0.92$

$\tau_{out,3} = 1.66$ N·m

6. EMBEDDED CONTROL AND GUI-BASED AUTOMATION:

i) ARDUINO-BASED CONTROL SYSTEM

The SCARA robotic arm is controlled using an Arduino microcontroller interfaced with a CNC shield, which provides structured connections for multiple stepper motor drivers. The Arduino generates STEP and DIRECTION signals to control NEMA 17 stepper motors through A4988 drivers, enabling precise joint-level motion. Micro stepping is configured to improve angular resolution and ensure smooth operation. Limit switches connected via the CNC shield are used for homing and boundary enforcement, enhancing positional repeatability and safety. A servo motor for gripper actuation is controlled using PWM signals from the Arduino. This control architecture provides a compact, low-cost, and reliable solution for coordinated multi-axis robotic motion.

Fig 5. Processing Code

ii) Graphical User Interface (GUI) for SCARA Robot Control

The SCARA robot employs a custom graphical user interface (GUI) developed using the Processing development environment, which facilitates both manual and automated control of the robot's motion. The GUI features controls for forward and inverse kinematics, allowing users to interactively set either joint angles or Cartesian coordinates for the end-effector. Using forward kinematics mode, users adjust sliders corresponding to each joint angle, and the GUI displays the resulting end-effector position in real time. In inverse kinematics mode, the desired Cartesian coordinates of the end-effector can be specified, and the GUI computes the corresponding joint angles required to achieve that position. This dual-mode interface enables intuitive motion input and enhances system usability. Furthermore, the GUI supports automation by allowing users to save multiple robot positions into a sequence and execute them in a loop, with configurable movement speed and acceleration.

Fig 6. Graphical User Interface

7. CONCLUSION

This work presented the design, development, and analysis of a low-cost SCARA robotic arm utilizing additive manufacturing and an Arduino-based control architecture. The mechanical structure was optimized through CAD modeling and fabricated using PETG material, which provided a balanced combination of strength, toughness, and printability suitable for functional robotic components. Analytical calculations of torque output, gear ratios, resolution, and load capacity confirmed that the selected stepper motors and belt–pulley transmission system deliver sufficient torque margins and positioning accuracy for reliable operation.

The embedded control system, implemented using an Arduino microcontroller in conjunction with a CNC shield and stepper motor drivers, enabled deterministic and coordinated multi-axis motion. The integration of a GUI as a supervisory control layer facilitated intuitive operation and process automation through forward and inverse kinematic control, reducing user complexity while enabling repeatable task execution. Experimental validation demonstrated stable motion, acceptable repeatability, and effective coordination between mechanical, electrical, and software subsystems.

Overall, the proposed system demonstrates that a cost-effective, 3D-printed SCARA robot with open-source control and GUI-based automation can achieve functional performance suitable for educational, research, and light industrial applications. The modular architecture also provides a foundation for future enhancements, including closed-loop feedback, advanced trajectory planning, and sensor-based automation.

8. REFERENCES:

1. Elsevier B.V., "Affordable SCARA robotic arm for small and medium manufacturing companies," *International Journal of Advanced Manufacturing Technology*, no. X, pp. 2459–2468, 2020.
2. H. V. Nguyen, V. D. Cong, and P. X. Trung, "Computer vision system integration with SCARA robot arm for pick-and-place operations," *Journal of Intelligent Manufacturing*, no. X, pp. 541–549, 2025.
3. Y. Ankara, H. Demir, A. Aydin, and C. Polat, "Design and production of a SCARA-type 3D FDM printer with three degrees of freedom," *Procedia Manufacturing*, pp. 127–140, 2018.
4. B. Kusigerski, M. Nikolov, D. Stojanovski, and A. Ivanoski, "Design and prototyping of a SCARA robotic arm with three degrees of freedom," *Mechanical Engineering Journal*, pp. 67–74, 2021.
5. P. Bhatia, R. K. Gupta, and S. Rajamanickam, "Expert system-based approach for SCARA robot design," *Engineering Applications of Artificial Intelligence*, pp. 99–109, 1998.
6. Y. C. Koo, M. M. S. Sauri, L. F. Tan, and Z. H. Chong, "Underactuated 3D printed SCARA robotic arm: kinematics and control," *Robotics and Computer-Integrated Manufacturing*, pp. 38–42, 2022.
7. M.-H. Hsueh, C.-J. Lai, W. H. Chen, and Y. C. Huang, "Characterization of PLA and PETG materials for fused deposition modeling under different loading conditions," *Materials Today: Proceedings*, pp. 1–11, 2020.
8. B. S. K. K. Ibrahim, A. M. A. Zargoun, R. El-Sayed, and K. Abdulrahman, "Modeling and control of a 4-DOF SCARA manipulator using

CAD and PID control," *International Journal of Mechanical Engineering and Robotics Research*, pp. 106–113, 2021.

9. D. Maneetham, P. Jirawattananukool, and S. Sirisomboon, "Workspace expansion of SCARA robot via linear sliding actuator," *Journal of Robotics*, pp. 1–9, 2017.
10. M. H. Liyanage, N. Krouglicof, R. Gosine, and S. R. Weerasinghe, "SCARA robotic arm for poultry deboning using hydraulic actuators," *Biosystems Engineering*, pp. 827–833, 2016.
11. M. H. Liyanage, N. Krouglicof, R. Gosine, and A. Fernando, "Affordable SCARA robotic arm as an alternative to CNC machines," *Journal of Manufacturing Systems*, pp. 1–13, 2017.
12. Y. I. Mohammed, S. M. Hussein, A. Abdulrahman, and R. S. Saleh, "Adaptive neuro-fuzzy inference scheme for SCARA robot control," *Applied Soft Computing Journal*, pp. 173–178, 2019.
13. M. Nkomo, M. Collier, R. Adams, and W. Moyo, "RGB color-sorting SCARA robotic arm using TCS3200 sensor," *International Journal of Advanced Robotic Systems*, pp. 763–769, 2015.
14. S. F. Noshahi, A. Farooq, M. Irfan, and H. R. Qureshi, "Design and fabrication of an affordable 4-DOF SCARA robotic manipulator," *International Journal of Mechanical and Mechatronics Engineering*, pp. 533–539, 2022.
15. F. G. Rossomando, C. M. Soria, D. Martinez, and L. F. Ortega, "Neuro-adaptive sliding mode control for SCARA robot arm," *Control Engineering Practice*, pp. 2556–2564, 2021.