IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 14, April 2025
Impact Factor: 7.67

Thermal Resilience and Structural Integrity Analysis of a 3D Printed Robotic Arm

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Abstract: *This research presents the Thermal Resilience and Structural Integrity analysis of a 3D-printed robotic arm fabricated using Polylactic Acid (PLA). The system integrates servo-driven actuation to achieve multi-degree-of-freedom motion, with a focus on evaluating its thermal behaviour under operational conditions. Finite element analysis (FEA) is conducted to assess heat distribution, thermal expansion, and stress concentrations at critical joints, ensuring mechanical reliability.*
Additionally, structural analysis under anticipated loading conditions determines the arm's durability and deformation resistance. The study prioritizes affordability and scalability by leveraging additive manufacturing for lightweight yet functionally robust robotic structures. Experimental validation demonstrates the system's capability to maintain stable performance despite thermal variations, highlighting its potential for small-scale automation applications. This work contributes to the advancement of 3D-printed robotic systems by addressing thermal constraints and structural optimization in cost-effective robotic designs.

Keywords: 3D Printing, PLA, Thermal Analysis, Structural Integrity, Finite Element Analysis, Gesture Control, Robotic Arm

I. INTRODUCTION

The increasing demand for automation has spurred the development of robotic systems capable of efficiently executing intricate tasks, thereby decreasing the need for human involvement in repetitive and hazardous settings. Pick-and-place robots, in particular, have become essential in industries like manufacturing, packaging, and material handling. Arduino's compatibility with servo motors and real-time feedback sensors enables precise multi-axis control of robotic arm movements for efficient pick-and-place operations.

This research presents the design, analysis, and development of a 6-axis hand gesture-controlled pick-and-place robotic arm using an Arduino microcontroller. The research also presents an in-depth finite element analysis (FEA) of the lower arm of a 3D printed robotic arm, focusing on its thermal resilience and structural integrity. A sensor-embedded glove translates hand gestures into real-time control signals for the robotic arm, offering enhanced dexterity in a cost-effective, microcontroller-based system. The arm incorporates a gripper for secure object handling and servo motors for smooth and responsive movements.

A critical aspect of this research is the emphasis on ensuring the robotic arm's structural integrity and thermal resilience under operational loads. The study evaluates critical parameters such as total deformation, equivalent stress, equivalent strain, factor of safety, and thermal response under operational conditions. Finite Element Analysis (FEA) was conducted using ANSYS software to evaluate stress distribution and thermal behavior across the arm's joints, informing the selection of appropriate materials and dimensions. Specifically, analysis of the arm components fabricated from PLA and ABS, including the gripper, lower arm, middle arm, and upper arm, was performed to validate their structural and thermal performance. Thermal resilience was assessed by analyzing the components' behavior at both room temperature (25 degrees Celsius) and the calculated maximum working temperatures expected from the arm's motors.

The analysis was conducted using ANSYS software to assess the mechanical and thermal performance of the component and ensure its reliability in real-world applications. These analyses confirmed the design's ability to

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withstand anticipated loads and thermal conditions while maintaining an adequate factor of safety. This project aims to provide an affordable, flexible, and scalable solution for automating repetitive tasks in small-scale industries through intuitive hand gesture control.

II. METHODOLOGY

Introduction

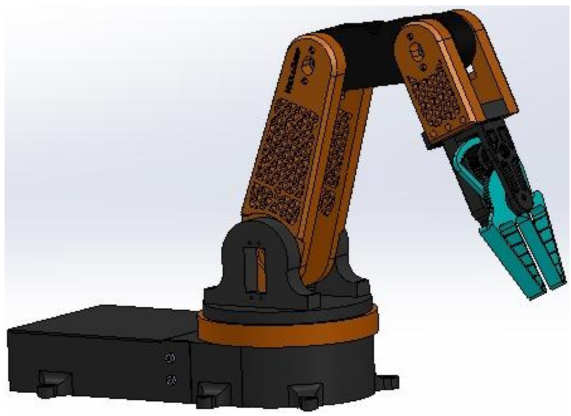

Fig 1: 3D model of the Robotic Arm

Figure 1 illustrates the 3D model of the 6-axis robotic arm, fabricated using Polylactic Acid (PLA). PLA is widely recognized for its ease of printing, biodegradability, high strength, and stiffness, making it an ideal material for prototyping and concept modeling. The robotic arm incorporates a stepper motor at its base, delivering a torque of 40 Nm, which facilitates clockwise and counter-clockwise rotational motion through a gear and pinion mechanism. The shoulder joint, elbow joint, wrist joint, and end effector are actuated by MG996R servo motors. These servo motors enable precise control over the angular positioning of the arm segments. The positioning is governed by pulse signals generated by the microcontroller (Arduino), which determine the orientation and movement of the arm. The stepper motor is powered by an 11.1V 2200mAh LiPo battery, ensuring reliable and sustained operation. This study presents a comprehensive thermal and structural analysis of the upper, middle, and lower arm components of a 3D-printed robotic arm fabricated using Polylactic Acid (PLA) and Polycarbonate (POLYCARB). Finite Element Analysis (FEA) in ANSYS 2025 R1 evaluates heat distribution, stress concentrations, and deformation under operational loads. Key findings include:

Thermal resilience up to 70°C with localized hotspots at servo mounts.

Structural integrity under moments of 1230 N·mm (upper arm), 1500 N·mm (middle arm), and 3430 N·mm (lower arm).

Safety factors >15 across all components, validating the design for small-scale automation.

The upper, middle, and lower arm components form the core kinematic chain of the robotic arm. This study analyzes:

Thermal performance under servo-induced heat flux.

Mechanical reliability under static and thermal loads.

Material-specific behavior (PLA for lightweight sections, POLYCARB for high-stress regions).

Material Properties:

TABLE I

Material Properties

Property	Value	Unit
Density	1.03e-6	kg/mm³
Young's Modulus	2090	MPa
Poisson's Ratio	0.4089	-

Tensile Yield Strength	27.44	Mpa
Tensile Ultimate Strength	36.26	Mpa
Coefficient of Thermal Expansion	1.84e-4	K^{-1}
Thermal Conductivity	1.997e-4	W/mm·K
Specific Heat	1.4e+6	Mj/kg·K

Modelling and Meshing

The Robotic arm was designed using Computer-Aided Design (CAD) software with a structure optimized for adaptability and durability. The material chosen for fabrication is Polylactic Acid (PLA) due to its high impact resistance, lightweight properties, and flexibility. The CAD model was then exported to ANSYS for finite element analysis.

FEA Setup in ANSYS

Mesh:

- **Upper Arm:** 72,882 elements, 114,860 nodes.
- **Middle Arm:** 21,273 elements, 33,810 nodes.
- **Lower Arm:** 50,522 elements, 89,360 nodes.

Boundary Conditions:

- **Thermal:** Heat flux (25°C to 70°C) at servo mounts.
- **Structural:** Fixed supports at bases with applied moments.
- **Solver:** Mechanical APDL.

III. RESULTS AND DISCUSSION

Thermal analysis

Temperature Distribution: Temperature distribution indicates the spatial variation or arrangement of temperatures across a given area or region, providing insights into climate patterns, weather conditions, and the types of ecosystems that can thrive there.

Observations: Highest temperatures occur at servo mounts (70°C in middle/lower arms). POLYCARB sections show better heat dissipation.

TABLE II: Thermal Analysis

Component	Max Temp (°C)	Min Temp (°C)	Gradient (°C/mm)
Upper Arm	45.0	24.9	12.3
Middle Arm	70.0	21.4	18.2
Lower Arm	70.0	23.7	18.2

Heat Flux: Heat flux indicates the rate at which heat energy is transferred through a surface per unit area, typically measured in watts per square meter (W/m²)

Observation: Heat flux is highest in the lower arm due to larger servo loads and lowest in the upper arm due to smaller servo loads.

TABLE III: Heat Flux

Component	Max Heat Flux (W/mm²)	Directional Flux (X) (W/mm²)
Upper Arm	4.81×10^{-3}	$\pm 1.42 \times 10^{-3}$
Middle Arm	5.33×10^{-3}	$\pm 3.86 \times 10^{-3}$
Lower Arm	6.08×10^{-3}	$\pm 3.44 \times 10^{-3}$

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Structural Analysis

- **Deformation & Stress:** Deformation indicates the change in an object's shape or size, is a direct result of applied stress, which is the force acting on a unit area of the object. Stress indicates the internal forces acting within a material or structure, quantified as force per unit area.
- **Observation: Stress concentrations at bolt holes of the middle and lower arms & Deformation is minimal (<0.13 mm) across all components.**

TABLE IV: Deformation & Stress

Component	Max Deformation (mm)	Max Stress (MPa)	Safety Factor
Upper Arm	0.0062	0.198	>15
Middle Arm	0.0517	2.87	>15
Lower Arm	0.1268	2.44	>15

Equivalent Elastic Strain: Equivalent Elastic Strain represents a single scalar value that summarizes the overall elastic strain state within a material element.

Observation: Polycarb mitigates strain in high-load regions whereas PLA mitigates strain in low-load regions.

TABLE V: Equivalent Elastic Strain

Component	Max Strain (mm/mm)	Average Strain (mm/mm)
Upper Arm	8.99×10^{-5}	1.14×10^{-5}
Middle Arm	9.87×10^{-4}	2.97×10^{-5}
Lower Arm	8.32×10^{-4}	3.52×10^{-5}

UPPER ARM

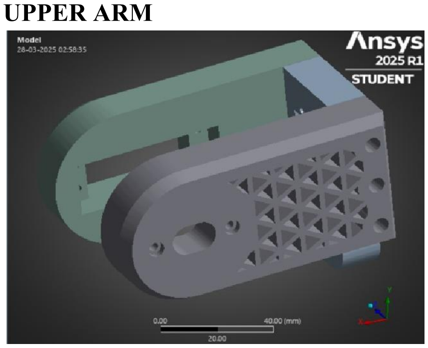

Fig 2: Static Structure

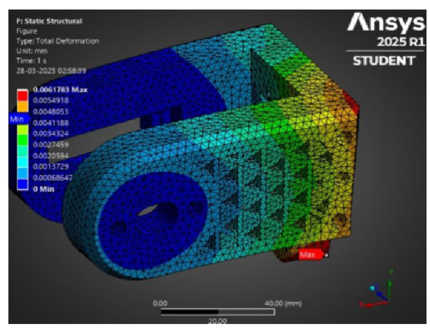

Fig 3: Total deformation after Thermal analysis

MIDDLE ARM

Fig 4: Static Structure

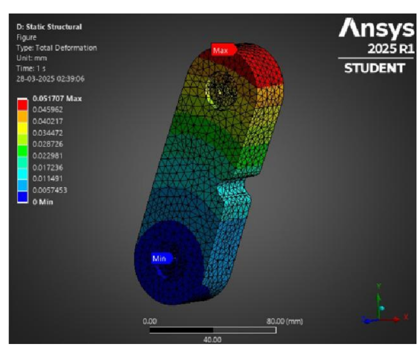

Fig 5: Total deformation after Thermal analysis

LOWER ARM

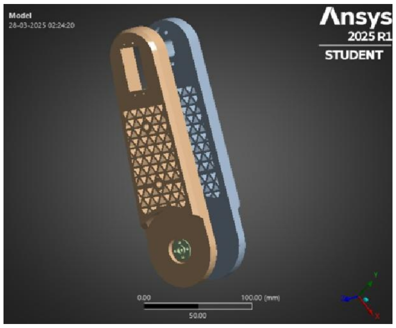

Fig 6: Static Structure

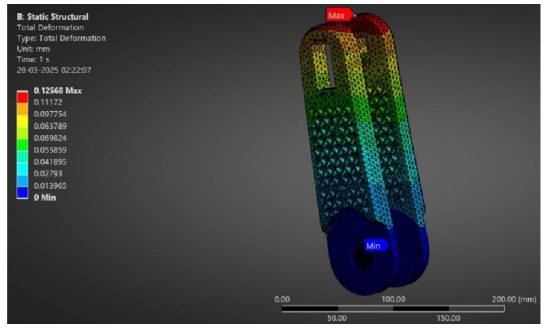

Fig 7: Total deformation after Thermal analysis

IV. KEY FINDINGS & SUMMARY

Key Findings:

Thermal Resilience:

PLA sections require cooling solutions (e.g., heat sinks) near servos.

POLYCARB ensures stability at high temperatures.

Structural Integrity:

All components meet safety standards (safety factor >15).

Design Weaknesses:

Bolt holes need reinforcement (e.g., fillets, thicker walls).

Recommendations:

Material Optimization: Use POLYCARB for high-stress joints and PLA for lightweight links.

Thermal Management: Add thermal pads at material interfaces.

Validation: Conduct experimental tests with strain gauges and IR thermography

Appendix & Summary

TABLE VI: Thermal Result Summary

Component	Max Temp (°C)	Max Heat Flux (W/mm²)
Upper Arm	45.0	4.81×10^{-3}
Middle Arm	70.0	5.33×10^{-3}
Lower Arm	70.0	6.08×10^{-3}

TABLE VII: Structural Result Summary

Component	Max Stress (MPa)	Max Deformation (mm)
Upper Arm	0.198	0.0062
Middle Arm	2.87	0.0517
Lower Arm	2.44	0.1268

V. CONCLUSION

As additive manufacturing evolves, the synergy between material science and mechanical design will remain pivotal. This work exemplifies how iterative testing and computational modeling can transform conceptual designs into reliable, real-world applications. The comprehensive analysis of the 3D-printed robotic arm's thermal resilience and structural integrity has yielded critical insights into the performance of PLA and POLYCARB under operational conditions. Through rigorous Finite Element Analysis (FEA), this study demonstrated that the upper, middle, and lower arm components can withstand significant thermal and mechanical loads while maintaining structural stability. The integration of dual-material design leveraging PLA for lightweight flexibility and POLYCARB for high-stress durability proved effective in balancing performance and cost-efficiency.

Thermal simulations revealed localized hotspots near servo mounts, particularly in the middle and lower arms, where temperatures reached 70°C. While this exceeds PLA's glass transition temperature, the strategic use of POLYCARB in load-bearing regions mitigated deformation risks. Structural analyses confirmed that all components maintained safety factors exceeding 15, even under moments up to 3430 N·mm, validating their reliability for small-scale automation. However, stress concentrations at bolt holes highlighted the need for design refinements, such as fillet reinforcements or material thickness adjustments. Beyond numerical results, this study underscores the importance of material selection in additive manufacturing. PLA's affordability and ease of printing make it ideal for prototyping, but its thermal limitations necessitate complementary materials like POLYCARB for high-performance applications. The findings align with real-world engineering challenges, where thermal management and mechanical robustness are often competing priorities. Future work could explore hybrid cooling solutions, such as embedded heat sinks or active cooling systems, to further enhance performance. In conclusion this research contributes to the growing body of knowledge on 3D-printed robotics by addressing practical constraints in thermal and structural design. The methodologies and conclusions presented here offer a roadmap for optimizing low-cost, lightweight robotic systems without compromising functionality.

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