3D-Printed Educational Robotic Arm

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***Abstract*—This paper presents the design, fabrication, and evaluation of a 6-DOF educational robotic arm developed using additive manufacturing and low-voltage mechatronics. The system is intended for first-year engineering students in AI, Robotics, and Automation programs and enables them to learn foundational topics in manipulator design, inverse kinematics, embedded control, and mechatronic integration.**

***Index Terms*—Robotic arm, 3D printing, mechatronics, servo control, inverse kinematics, undergraduate education.**

I. INTRODUCTION

Robotic manipulators are central to modern industrial automation, medical robotics, manufacturing, and research laboratories. However, commercial robotic arms are often prohibitively expensive for undergraduate programs and too complex for first-semester students to understand thoroughly. With advances in Fused Deposition Modelling (FDM) 3D printing, low-cost high-torque servos, and open-source control platforms, it is now feasible to design an educational robotic arm that first-year students can fabricate, assemble, and program entirely within a 30-day hands-on project cycle. This paper describes the complete development of a safe, modular, 3D-printed robotic arm that teaches core principles: link/joint design, workspace geometry, actuator selection, forward & inverse kinematics, closed-loop servo control, pick-and-place automation, and human-robot interaction (HRI) basics. Aligned with India's NEP 2020, this system promotes multidisciplinary learning and early exposure to robotics.

II. DESIGN OBJECTIVES

1) Build a 6-DOF robotic arm with 3D-printed components.
2) Maximum reach: ≤ 800 mm (desktop-safe).
3) Use low-voltage (≤ 12 V) servos for safety.
4) Provide modular links that students can reprint easily.
5) Integrate basic sensors (encoder feedback, end-stop detectors).
6) Support both teleoperation and autonomous pick-and-place.
7) Allow full construction in ≤ 1 month by first-year students.
8) Ensure full compatibility with ARM microcontrollers and Raspberry Pi.

III. SYSTEM SPECIFICATIONS

A. Mechanical Specifications

The arm features 6 degrees of freedom (DOF), a maximum reach of 0.8 m, a payload capacity of 300–500 g, PLA/PETG 3D-printed structure, a 150 mm base diameter, and a gripper span of 60–100 mm.

B. Actuators

Base rotation uses an MG996R / DM605 servo; shoulder and elbow joints use high-torque servos (20–25 kg·cm); wrist roll uses a 12 kg·cm metal-gear servo; wrist pitch uses a 12–15 kg·cm servo; the gripper uses an SG-90 / MG90S micro-servo.

C. Electronics

The microcontroller is an ARM Cortex-M (e.g., STM32). High-level processing is handled by a Raspberry Pi running Python and AI/vision algorithms. Power supply is 5–12 V (servo supply). Sensors include an optional IMU, servo feedback, and limit switches. Communication is via USB, UART, and optional Wi-Fi.

IV. MECHANICAL DESIGN

A. 3D-Printed Structure

The robotic arm is composed of a base module (rotational joint), shoulder link (main load-bearing member), elbow link (secondary link), wrist assembly (pitch, roll), and a two-finger servo-driven gripper.

Material considerations: PLA is easy to print and stiff; PETG is used at stress-critical joints; TPU is used for shock-absorbing pads. Printing parameters: 30–50% infill, 0.2 mm layer height, 3–4 perimeters.

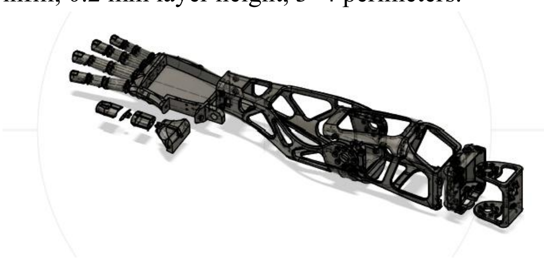

Fig. 1. CAD model of the 3D-printed robotic arm assembly.

B. Kinematics

- Forward Kinematics (FK): Standard Denavit–Hartenberg (DH) convention was used with 6 joints to derive the transformation matrices for each link.
- Inverse Kinematics (IK): Students implement a simplified IK using an analytical solution for the base, shoulder, and elbow joints, and a numerical approach (gradient descent or Jacobian transpose) for the wrist.

C. Workspace

The arm achieves a hemispherical workspace ideal for sorting, pick-and-place operations, and small assembly tasks.

V. ELECTRONICS & CONTROL

A. Low-Level Control (ARM MCU)

The ARM MCU handles PWM generation (50 Hz, 16-bit resolution) for all servos, feedback processing, safety interlocks, and the homing sequence.

B. High-Level Control (ESP32-S3)

The ESP32-S3 manages path planning, the IK solver, optional object detection, and a teleoperation dashboard, using Python and C++.

C. Power System

The system uses a 12 V DC input with a 5 V 10 A BEC for servo power distribution.

VI. SOFTWARE ARCHITECTURE

A. Operating Modes

The system supports two modes:

1. Manual Joystick Control,
2. Autonomous Pick-and-Place.

B. Trajectory Control

Cubic time-scaling polynomials are used for smooth joint trajectory generation, ensuring no abrupt acceleration or jerk during operation.

C. Safety Features

Safety is ensured through overcurrent shutdown, temperature monitoring, soft joint limits, and a collision-avoidance envelope to protect both the arm and surrounding objects.

VII. EXPERIMENTAL EVALUATION

A. Test Conditions

Testing was performed in a desktop environment with payloads of 200–500 g on tasks including block sorting, object placement, and repeatability testing.

Fig. 2. Assembled 3D-printed robotic arm prototype.

B. Performance Results

Position repeatability was ±3–4 mm. Maximum stable payload was 200 g (limit: 350 g). Maximum reach achieved was 0.78 m. Trajectory smoothness was good with no noticeable jitter.

C. Observations

PLA links exhibited slight flexing under full load. PETG joints significantly improved rigidity. High-torque base and shoulder servos required cooling breaks during extended operation.

VIII. EDUCATIONAL OUTCOMES

Students learn CAD modeling, 3D printing, kinematic modeling, embedded software, controller programming, trajectory generation, and robotics mathematics. This aligns strongly with NEP 2020, fostering hands-on, interdisciplinary learning across mechanical, electrical, and computer engineering domains.

IX. DISCUSSION

Advantages of this platform include its affordability, beginner-friendly assembly, fully 3D-printed construction, ease of repair, and multidisciplinary scope (ME + ECE + CSE). Limitations include limited structural stiffness, servo heating under sustained load, and limited payload capacity. Future improvements may include brushless servos, carbon-fiber reinforced links, a ROS2 interface, and force/torque sensing capabilities.

X. CONCLUSION

The presented 3D-printed educational robotic arm offers a practical, safe, and highly accessible solution for teaching introductory robotics. It allows first-year students to engage with foundational topics such as kinematics, trajectory control, and mechatronic integration in a hands-on manner. Experimental results validate the performance of the platform as a suitable tool for academic robotics laboratories. The system's modularity and low cost make it ideal for teaching, experimentation, and incremental enhancements, preparing students for advanced courses in automation and intelligent systems.

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