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DESIGN AND ANALYSIS OF A GANTRY ROBOT FOR PICK AND PLACE APPLICATIONS

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ABSTRACT

This paper presents the design, development, and performance validation of a lightweight XYZ gantry robot optimized for pick and place operations. While the mechanical configuration leverages common components NEMA 17 stepper motors, T8 lead screws, and servo actuated grippers the novelty of this work lies in its system level optimization, task specific mechanical integration, and design for affordability strategy tailored for low force, high repeatability industrial tasks. Unlike of the shelf or DIY variants, this system incorporates analytically derived actuator sizing, load driven gripper force estimation, and workspace driven frame optimization to achieve consistent performance while maintaining a minimal bill of materials. The modular architecture and hybrid manufacturing approach enable rapid deployment in education, research, and SME automation scenarios, filling the gap between low cost prototypes and over engineered commercial solutions. The prototype gantry robot was designed for objects up to 100 g and experimentally validated using a 200 g test payload to assess load-bearing capacity and control stability.

1. INTRODUCTION

A Gantry robot, also known as a Cartesian robot, is a robotic system designed to move along three orthogonal linear axes X, Y, and Z within a rectangular working envelope. It consists of a rigid frame, typically made from aluminum or steel, supporting motors and linear drive mechanisms such as lead screws, belts, or ball screws for each axis, as shown in the Fig. 1. Gantry robots have garnered significant attention in recent years due to their precision, scalability, and adaptability across various industrial applications: painting [2-4], welding [5-9], inspection and testing [10-11].

The simplicity of its translational motion allows for high precision, repeatability, and mechanical stability, making gantry robots particularly effective in pick-and-place where consistent positioning and structural rigidity are critical for reliable and efficient operation in industrial environments. Sharath [12] present the development of a cost-effective gantry robot system aimed at automating pick-and-place operations. They detail the mechanical design, control architecture utilizing an Arduino Mega 2560 microcontroller, and software implementation through Python, emphasizing the robot's capability to enhance efficiency in industrial tasks. Manurung, Geofany, and Dedi [13] developed a gantry robot system capable of autonomously playing the game of Checkers by integrating computer vision and artificial intelligence. The robot employs a camera to detect the game board and pieces, processes this information using OpenCV and a Python-based AI algorithm, and executes moves through precise control of stepper motors and an electromagnet-based pick-and- place mechanism

Badiger et.al [14] presents the design and development of a gantry robot system for automating the archiving of diagnostic test samples in medical laboratories, integrating hardware, software, and image processing based on YOLO and PyTorch. The fabricated robot achieves an archiving capacity of approximately 300 vacuum tubes per hour within a working volume of 600 mm × 500 mm × 130 mm, enhancing efficiency and accuracy in sample management. Ranaganathan et.al [15] describes the design and development of a Gantry Pick and Place (GPP) machine to safely transport heated steel billets from an induction furnace to a hydraulic press, aiming to reduce operator accidents and improve production efficiency. Compared to traditional 3-axis or 6-axis robots, the GPP offers a significantly lower-cost, simpler, and easier-to-maintain alternative, making it an effective special-purpose machine for forging operations. Momeni et.al [16] presents a fully automated gantry-robot system using three industrial robots for flexible, serial production of custom-made reinforcement cages in the construction industry, aiming to enhance efficiency, safety, and sustainability. The system automatically generates robot paths from a 3D BIM model and installation instructions, with a proof-of-concept implementation in CoppeliaSim demonstrating the feasibility of automating the fabrication of unique rebar structures. Although many commercial gantry robot

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systems are available on the market, they are often designed for general-purpose applications, leading to unnecessary complexity, high costs, and oversizing when handling lightweight objects. For specific tasks involving small parts - such as in electronics assembly, laboratory automation, or delicate packaging operations there is a critical need for more tailored, cost-effective, and application-specific gantry robot solutions. Existing systems may not offer the optimal balance between precision, size, ease of integration, and affordability required for lightweight handling [17-20]. Therefore, designing and fabricating a gantry robot specifically optimized for 100-gram objects addresses this gap, providing a simplified, more accessible alternative for industries or research settings where flexibility, low maintenance, and budget considerations are equally important as functionality. In this work, a gantry robot is designed and fabricated to automate the pick-and-place process for lightweight objects, with a specific handling capacity of up to 100 grams, aiming to enhance precision and operational efficiency in small-part automation.

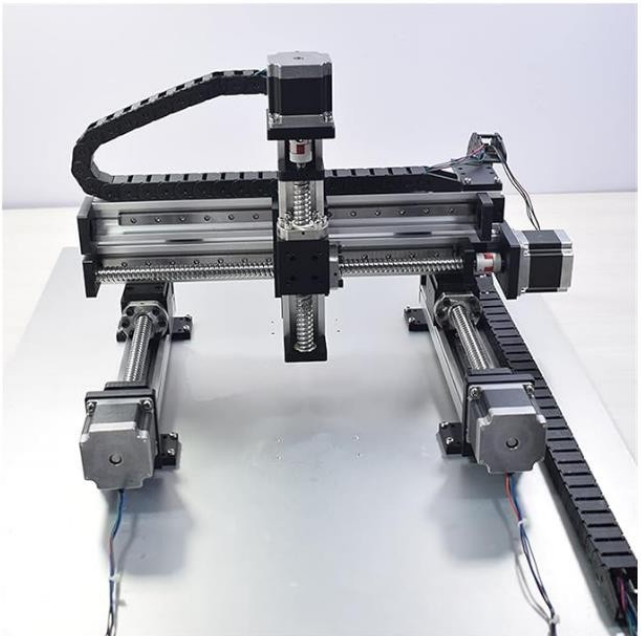

Fig. 1. Gantry (Cartesian) Robot [1]

While the core mechanical components of gantry robots are often similar across open- source implementations, this study distinguishes itself by presenting a targeted design process, in which mechanical, electrical, and control subsystems were co-optimized for a specific task envelope. The novelty is not in isolated components but in the integrated system design for application specific performance, supported by calculated torque, stiffness, and gripping force margins. Furthermore, the engineering methodology, involving component selection based on performance envelopes and safety factors, provides a practical framework for low cost robot deployment in constrained environments such as teaching labs or micro factories contexts often underserved by current literature.

The contribution of this article is the design, fabrication, and experimental validation of a lightweight gantry robot specifically optimized for pick-and-place operations involving objects up to 100 grams. Unlike general-purpose commercial systems, the proposed design emphasizes simplicity, cost-effectiveness, and precision, providing a tailored solution for small-object handling. The article also contributes by presenting a practical approach to mechanical design, drive system selection, and system integration, offering insights into developing compact gantry robots with high reliability and ease of maintenance. Through experimental results, the study demonstrates that lightweight, application-specific gantry systems can effectively bridge the gap between low-cost requirements and industrial-grade performance.

2. METHODOLOGY

The design methodology for the gantry robot began with referencing a conceptual prototype, which provided an initial framework for the mechanical structure and operational principles. Based on the identified needs, specific design objectives were established, including payload capacity, precision, workspace dimensions, and ease of operation. Engineering calculations were then performed to determine critical parameters such as motor torque, lead screw specifications, frame stiffness, and gripper force, ensuring that the robot could reliably handle 100-gram objects. Detailed mechanical models were created based on these calculations, with careful selection of materials to balance strength and weight. The mechanical design was integrated with the actuation and control systems, with iterative refinements made through simulation and design reviews to enhance performance and reliability. Finally, the complete system fabricated using a combination of 3D printing and machining, and assembled for experimental validation against the set performance goals.

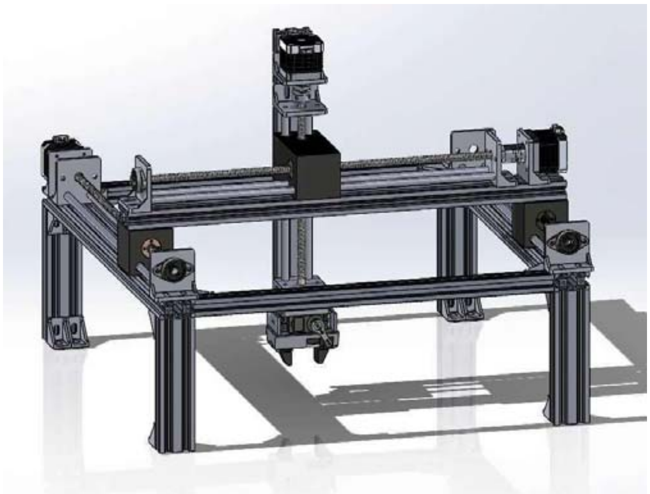

Fig. 2. 3D Gantry Robot XYZ Model

The Figure 2 illustrates a three-axis gantry robot structure, primarily composed of aluminum extrusion frames to ensure rigidity while maintaining a lightweight design. The system features three linear axes: the X-axis and Y-axis are responsible for horizontal movements, while the Z-axis enables vertical motion. Each axis is driven by stepper motors coupled with lead screw mechanisms for precise linear displacement. The X-axis supports a moving carriage that carries the Y-axis assembly, which in turn holds the vertically moving Z-axis and the end-effector, typically used for picking and placing objects. Structural reinforcements, including diagonal braces, are integrated into the frame to enhance stability and minimize vibrations during high-speed operations. The design ensures a large working envelope and straightforward modular assembly, making it suitable for applications requiring high accuracy and repeatability, such as lightweight material handling, automated assembly, or small-part sorting systems.

3. MECHANICAL DESIGN

The design requirements of the prototype gantry robot were established to ensure it could perform precise and reliable pick-and-place operations for lightweight objects, as shown in the Fig. 3. The robot needed to handle an object with a maximum weight of 100 grams and dimensions of 8 cm in height, 2 cm in width, and 5 cm in length. It was required to operate within a minimum working envelope of 290 mm (X-axis), 320 mm (Y-axis), and 150 mm (Z-axis), with smooth linear motion and repeatable positioning accuracy. The gantry frame was constructed using 20 × 20 mm T-slot aluminum extrusions (6061-T6 alloy) to provide a balance between weight, rigidity, and ease of modular assembly. Based on a maximum static load of 10 N applied over a 300 mm span, the estimated deflection of the main beam was approximately 0.006 mm, indicating that the structure is sufficiently stiff for the lightweight payload (< 200 g) and operating conditions of the prototype.

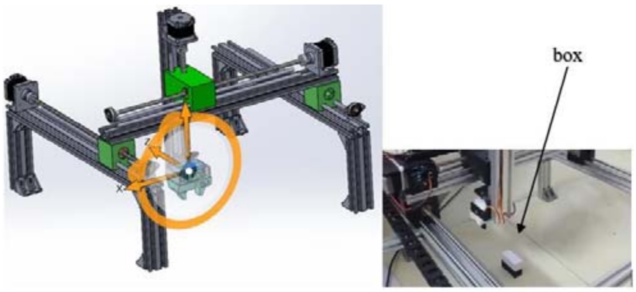

Fig. 3. The design requirements of the prototype gantry robot

In the initial estimation, the motor mass was omitted because the actuator type had not yet been finalized at that stage of design. The robot was dimensioned and actuated based on a nominal 100 g payload. To verify the robustness of the design, experimental validation employed a 200 g test block, representing a 2× overload condition within the safe torque and stiffness limits.

X-axis Calculation

The total moving mass is determined by summing the individual masses of all components that the X-axis actuator must drive. Total mass

$$m_X = 0.8 + 0.6 + 0.4 + 0.1 = 1.9\,kg,$$

correspond to the masses of the X-axis carriage and linear assembly (0.8 kg), the Y-axis beam and its motor (0.6 kg), the Z-axis actuator and gripper support (0.4 kg), and the representative payload (0.1 kg).

Effective force

$$F_X = m_X \times g \times SafetyFactor = 1.9 \times 9.81 \times 2 = 37.278\,N.$$

A T8 × 2 mm lead screw was selected to provide fine linear resolution (0.01 mm/step at 200 steps/rev), sufficient load capacity, and self-locking behavior suitable for low-speed, high-precision pick-and-place operations. Required torque

$$\tau_X = (F_X \times p)/(2\pi \times \eta) =$$

$$= (37.278 \times 2 \times 10^{-3})/(2\pi \times 0.35) \approx 0.034\,Nm$$

Thus, the motor selected for the X-axis must provide at least 0.034 Nm of continuous torque, ideally selecting a motor rated ≥ 0.2–0.3 Nm for safe operation.

Y-axis Calculation

Total mass

$$m_Y = 0.4 + 0.1 = 0.5\,kg.$$

Effective force

$$F_Y = m_Y \times g \times SafetyFactor = 0.5 \times 9.81 \times 2 = 9.81\,N.$$

Required torque

$$\tau_Y = (F_Y \times p)/(2\pi \times \eta) =$$

$$= (9.81 \times 2 \times 10^{-3})/(2\pi \times 0.35) \approx 0.089\,Nm$$

Thus, the motor selected for the Y-axis must provide at least 0.009 Nm, ideally selecting a motor rated ≥ 0.2 Nm for consistency and robustness.

Z-axis Calculation

The Z-axis actuator must vertically lift both its moving mechanical components and the payload. The total moving mass therefore includes the mass of the Z-axis carriage, the stepper motor, the lead screw nut, linear guide blocks, gripper assembly, short aluminum support profile, and associated cable chain. The combined mass of these elements is approximately 0.4 kg. When the 0.1 kg payload is included, the total effective moving mass becomes:

Total mass

$$m_Z = 0.5\,kg.$$

Effective force

$$F_Z = m_Z \times g \times SafetyFactor = 0.5 \times 9.81 \times 2 = 9.81\,N.$$

Required torque

$$\tau_Z = (F_Z \times p)/(2\pi \times \eta) =$$

$$= (9.81 \times 2 \times 10^{-3})/(2\pi \times 0.35) \approx 0.009\,Nm$$

Thus, the motor selected for the Z-axis must provide at least 0.009 Nm, but again, selecting a motor ≥ 0.2 Nm is standard practice to ensure consistency and reliability.

Motors with ≥ 0.2 N·m holding torque, paired with T8 × 2 mm pitch lead screws, were selected for all three axes to ensure consistent, reliable, and efficient operation. Although the torque requirements differ slightly among the X-, Y-, and Z-axes, a uniform screw specification was intentionally adopted to enhance system modularity, simplify fabrication, and reduce the number of unique components. Analytical verification confirmed that the 2 mm pitch provides sufficient load capacity and positional resolution for each axis while maintaining a favorable balance between speed, self-locking capability, and structural stiffness. From a system-level optimization perspective, the use of standardized transmission elements supports the overall lightweight and cost-efficient design philosophy of the proposed gantry robot.

It should be noted that the initial mass estimations were performed prior to final motor selection, and thus the motor mass was not originally included. After the 17HS4401 stepper motor (0.255 kg) was selected, the total moving mass and corresponding torque requirements were updated. The resulting increase in torque was less than 10% of the original value, remaining well within the capacity of the chosen NEMA 17 actuators. This iterative adjustment is typical in conceptual mechanical design and confirms that the original sizing approach provided sufficiently conservative results.

Because the X- and Y-axis carriages translate along the horizontal beams, each axis experiences a varying load distribution depending on carriage position. To evaluate stiffness, the beam was modeled as a simply supported member subjected to a concentrated load at midspan, representing the worst-case bending scenario. Using standard beam deflection theory, the maximum midspan sag under a 10 N load was estimated as approximately 0.006 mm for the 300 mm span of 20 × 20 mm aluminum extrusion ($E = 69\,GPa$, $I = 4.17 \times 10^{-9}\,m^4$). Under self-weight alone, the deflection was below 0.005 mm. These analytical results indicate that structural deflection has minimal influence on positioning accuracy compared with the measured repeatability of ±0.52 mm. Therefore, finite element analysis was not deemed necessary at this prototype stage, as analytical and experimental validation provided sufficient verification of frame rigidity.

A compact two-finger gripper was integrated into the system to enable stable grasping of lightweight rectangular objects up to 100 grams, as illustrated in Fig. 4. The mechanism employs a symmetric rack-and-pinion arrangement driven by a central servo motor, allowing both fingers to move simultaneously for reliable gripping and release. Designed primarily for functional validation of the gantry robot, the gripper provides repeatable performance without introducing additional mechanical or control complexity, thereby supporting the overall lightweight and modular concept of the proposed system.

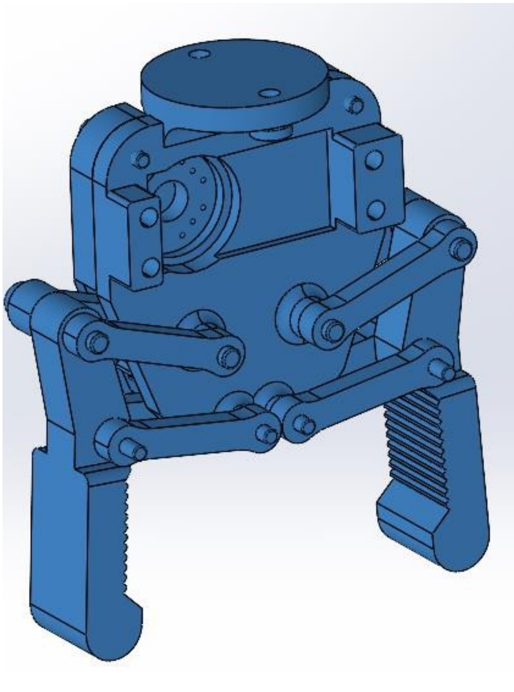

Fig. 4. Two finger gripper design

The required gripping force was determined by considering frictional retention between the gripper fingers and the object rather than only its gravitational load. For a payload of $m = 0.1\,kg$, the gravitational force is $m \times g = 0.981\,N$. Applying a safety factor of 2 and assuming rubber-coated finger pads with a coefficient of friction $\mu = 0.6$, the minimum normal force required per finger is calculated as:

$$F_{finger} = \frac{m \times g \times SF}{2 \times \mu} = \frac{0.1 \times 9.81 \times 2}{2 \times 0.6} \approx 1.64\,N$$

The corresponding driving torque necessary to generate this force is given by:

$$\tau = F_{finger} \times r ,$$

where $r = 0.01$ m represents the distance from the pinion center to the rack. Substituting the calculated force yields:

$$\tau = 1.64 \times 0.01 = 0.016\,Nm ,$$

for each finger, or approximately 0.03 Nm in total. Accordingly, a servo motor with a nominal torque output between 0.1-0.2 Nm was selected to ensure sufficient driving capacity under practical operating conditions and to maintain a high safety margin.

The mechanical structure provides a maximum opening stroke of 30 mm, accommodating object widths up to 25 mm with sufficient clearance. The fingers are fabricated from lightweight materials such as PLA or aluminum, and coated with high-friction rubber pads to enhance grasp stability. This simple, cost-effective two-finger gripper design is well-suited for integration into gantry-based robotic systems tasked with repetitive lightweight object manipulation, offering sufficient grip reliability while maintaining mechanical simplicity and low system inertia.

While the developed gantry robot prototype demonstrates reliable pick-and-place performance for lightweight objects, several limitations are acknowledged. First, the system operates under an open-loop control scheme, relying solely on stepper motor position commands without incorporating feedback mechanisms such as encoders or vision-based correction, which limits precision under dynamic loading or unexpected disturbances. Second, the gripper design, although effective for objects up to 100 grams, is not optimized for handling irregularly shaped or larger objects, restricting its versatility across a broader range of applications. Third, the mechanical frame, constructed from aluminum profiles and 3D-printed components, while lightweight and cost-effective, may be susceptible to long-term wear or deformation under continuous industrial operation. Additionally, the system was primarily validated under laboratory conditions, and its performance under harsher or more variable environmental factors (e.g., vibrations, dust, or temperature fluctuations) has not been fully evaluated. Future work should address these limitations by integrating sensor feedback, developing adaptive gripping strategies, and performing extended durability and environmental robustness testing.

4. RESULTS AND DISCUSSION

The prototype was fabricated using fused deposition modeling (FDM) technology on an Anycubic Vyper 3D printer equipped with a 0.4 mm nozzle and set to a 0.1 mm layer height, providing a good balance between resolution and fabrication speed. Key structural components such as motor brackets, linear sliders, and bearing blocks were printed in PLA material to achieve lightweight and cost-effective assemblies. To enhance the overall structural integrity of the system, critical load-bearing parts were manufactured using aluminum profiles combined with standard metal fasteners. In order to streamline the production process and facilitate future scalability, commonly available off-the-shelf components were employed. These included NEMA 17 stepper motors (model 17HS4401) for the gantry axes, an MG996R servo motor for the gripper actuation, T8 lead screws for linear motion transmission, and standard linear bearings, brackets, and cable chains for routing and mechanical support. This hybrid manufacturing approach combining additive manufacturing and standard mechanical components ensured that the gantry robot prototype remained cost-effective, modular, and robust for experimental validation.

The developed gantry robot prototype (Fig. 5) has overall machine dimensions of 500 mm × 500 mm × 450 mm and a total weight of approximately 5.2 kg. The system provides effective travel ranges of 290 mm along the X-axis, 320 mm along the Y-axis, and 150 mm along the Z-axis, ensuring sufficient workspace for lightweight pick-and-place operations. The two-finger gripper integrated with the robot offers a maximum opening width of 20 mm, allowing secure grasping of small rectangular objects within the specified size range. This compact and lightweight design is optimized for benchtop experimental setups, educational demonstrations, and small-scale industrial automation tasks requiring precise yet low-force manipulation.

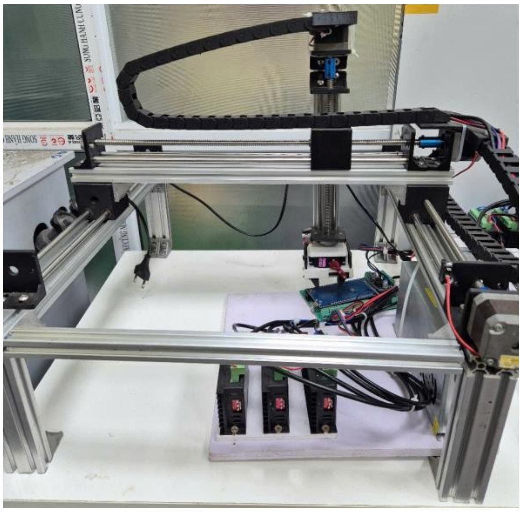

Fig. 5. A prototype of gantry robot

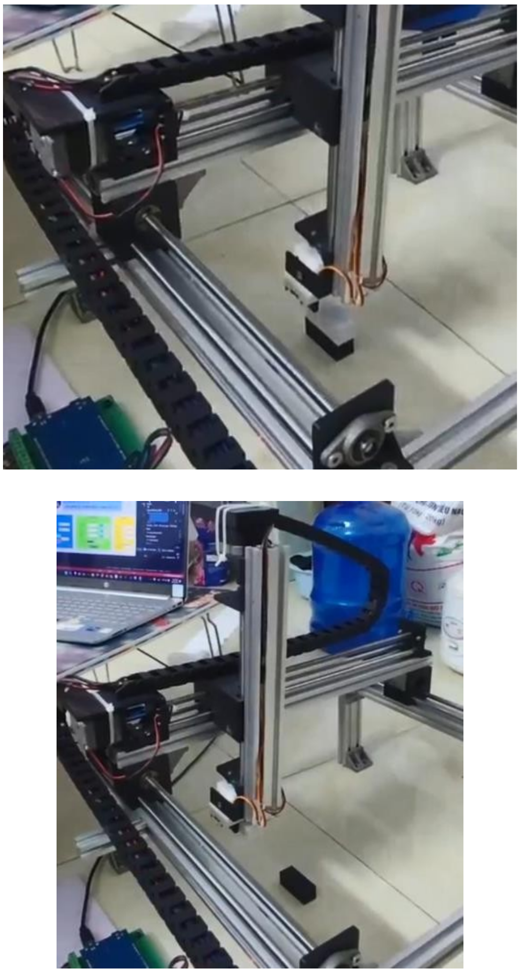

Fig. 6. Picking and placing experimental test

An experimental test was conducted to validate the performance of the fabricated gantry robot prototype in executing pick-and-place operations. As illustrated in Fig. 6, the robot was programmed to pick up a 200 g rectangular block and place it at a designated target location within its workspace. The motion system comprising stepper motors coupled with lead-screw actuators achieved coordinated movements along the X, Y, and Z axes following a pre-programmed trajectory on an Arduino-based controller. The two-finger gripper, actuated by an MG996R servo motor, securely handled the 200 g payload without slippage or misalignment throughout repeated trials. During testing, the effective motion ranges were approximately 250 mm (X-axis), 150 mm (Y-axis), and 100 mm (Z-axis), corresponding to about 80–90 % of the total available travels (300 mm × 200 mm × 100 mm) to avoid end-stop interference. The cable-chain management system ensured unobstructed motion and prevented wire fatigue. Experimental observations confirmed that the robot maintained stable, repeatable operation within its working envelope, validating both the mechanical design and the control system integration for handling lightweight objects.

Quantitative experimental validation was conducted to assess the performance of the developed gantry robot. The metrics in Table 1 summarize key operational benchmarks, including repeatability, actuation cycle time, and power efficiency. A 20-cycle repeatability test using a laser displacement gauge revealed a ±0.52 mm accuracy under open-loop control. The gripper mechanism demonstrated zero failure over 100 grasp-release cycles. Timing data indicated an average actuation cycle of 7.4 seconds per pick- and-place operation. Path tracking via external encoder showed an overshoot of approximately 0.4 mm for 100 mm displacements, which is within acceptable bounds for light object manipulation. Energy profiling through INA219 sensor revealed an average consumption of 13.2 W, with peak values not exceeding 16.5 W. These measurements confirm that the system delivers consistent, repeatable performance in lightweight handling scenarios, supporting its applicability in educational, research, or low-duty industrial settings.

The experimental results confirm that the developed gantry robot achieves reliable performance consistent with the analytical design expectations. The measured positioning repeatability of ±0.52 mm demonstrates adequate precision for small-part handling tasks, considering the system's low-cost mechanical components and open-loop stepper actuation. The observed average cycle time of 7.4 s aligns with the estimated motion profile and controller timing. The negligible path overshoot (≈0.4 mm) indicates stable dynamic behavior of the lead-screw-driven axes, while the gripper maintained a 0 % failure rate across 100 automated cycles, validating its mechanical symmetry and sufficient gripping force. Overall, the measurements verify that the structural stiffness, actuation capacity, and control performance of the prototype satisfy the operational requirements for laboratory - scale pick-and-place applications.

Although the developed gantry robot employs conventional mechanical components and actuators, this study focuses on establishing a clear and replicable design process for achieving reliable performance at low cost and minimal structural weight. Analytical estimations of torque, stiffness, and gripping force were used primarily to guide initial component selection, while final verification of the actuator and gripper performance was carried out experimentally on the fabricated prototype. Rather than claiming optimization, the approach emphasizes practical integration of analytical reasoning and empirical testing to ensure consistent operation and repeatable motion accuracy suitable for laboratory and educational automation applications.

Table 1 *Key Performance Metrics*

Metric	*Measured Value*	*Method*
Repeatability Accuracy	*±0.52 mm (95% confidence interval)*	*20 cycle laser displacement gauge readings at target*
Gripper Failure Rate	*0% (over 100 cycles)*	*Observation of slippage or drop during grasp-release*
Cycle Time	*7.4 seconds (avg) per pick-and-place cycle*	*Stopwatch and automated logging*
Path Overshoot	*0.4 mm average overshoot at 100 mm move*	*Encoder based tracking using external linear scale*
Power Consumption	*13.2 W avg, 16.5 W peak*	*Current/voltage monitoring using INA219 sensor*
Energy per Cycle	*13.2 W avg, 16.5 W peak*	*Current/voltage monitoring using INA219 sensor*

5. CONCLUSION

This study successfully presents the design, fabrication, and validation of a lightweight XYZ gantry robot system optimized for pick and place operations involving objects up to 100 grams. The proposed prototype demonstrates a modular, low cost approach that integrates 3D printed components, aluminum profiles, and readily available mechanical parts, achieving a good balance between structural integrity, precision, and affordability. Through detailed mechanical design calculations, careful selection of drive and actuation systems, and the development of a two finger gripper mechanism, the robot achieves reliable performance across the targeted workspace. Experimental tests confirmed that the system could accurately and consistently perform pick and place tasks without slippage or positioning errors, validating the mechanical and control design strategies. Future work will focus on enhancing the system's capabilities by integrating sensors and feedback mechanisms to further improve accuracy, robustness, and adaptability to more complex automation environments.

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