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XYZ Gantry: A PLC-Based Automated Pick-and-Place Robot for Precision Handling

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***Abstract*—Abstract-The XYZ gantry system is an automated solution designed for precise, coordinated movement along three orthogonal axes (X, Y, Z), commonly used in pick-and-place applications. Integrated with a PLC for seamless control, it enhances productivity, reduces costs, and improves accuracy in industrial tasks like material handling and assembly. Featuring a robust structure, high-precision motors, and advanced motion control, the system supports scalable, flexible automation. Its implementation drives technological innovation, creates skilled jobs, and promotes energy-efficient, sustainable manufacturing practices. This study focuses on the design, development, and industrial applications of the XYZ gantry system in modern automation**

***Keywords* — PLC, Gantry, Precision Robot, Automation**

I. INTRODUCTION

Fig.1. Figure of Gantry System

A gantry system using XYZ coordinates is a versatile mechanical setup that delivers high precision along three linear axes: X, Y, and Z. This system is widely used in automation, robotics, CNC machining, 3D printing, and other industrial applications where accurate and coordinated movement is essential. Operating within a Cartesian coordinate system, the XYZ gantry provides the advantage of easy movement across a three-dimensional spatial plane. Its design, consisting of a rigid frame, stepper or servo motors, linear guides for smooth travel, and a control system to synchronize motor actions, makes it ideal for tasks requiring high accuracy, such as material handling, assembly, and machine manipulation

When coupled with PLCs, the capabilities of XYZ gantry systems expand significantly. PLCs act as the brain of the system, coordinating and synchronizing the movements of the gantry's motors across all three axes. With a PLC controlling the system, real-time feedback mechanisms ensure that the gantry can adjust its movements on-the-fly based on various factors such as changes in load, variations in material properties, or external influences. This dynamic control ensures that even in high-speed, high-volume production environments, the system can maintain accuracy and prevent errors. The PLC's programming flexibility allows operators to easily modify movement paths, speeds, and sequences to optimize the gantry system for different tasks, whether it's for picking and placing small parts in an assembly line or for machining large, heavy work pieces in a factory setting. Furthermore, PLCs enable sophisticated fault detection, which helps to identify potential issues before they cause disruptions, improving uptime and minimizing downtime. By integrating XYZ gantry systems with PLCs, manufacturers can significantly enhance their production efficiency, reduce material waste, improve quality control, and ultimately lower operational costs, making them a critical component in the automation of modern manufacturing processes.

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A key feature of XYZ gantry systems in automation is the integration of proximity sensors, which play a critical role in precise positioning and obstacle detection. These sensors allow the gantry to detect objects or surfaces within close range, ensuring that movements are executed with high accuracy. Proximity sensors can be used for positioning the gantry at specific locations, providing feedback to the PLC for fine adjustments and ensuring that the system aligns with the correct coordinates. Additionally, these sensors are essential for obstacle detection, preventing collisions with nearby objects or barriers during the system's operation. This enhances safety and reliability, particularly in environments where the gantry must navigate complex workspaces. The combination of precise positioning and real-time obstacle detection further optimizes the gantry system's performance, making it an indispensable tool in industries that require high efficiency, safety, and minimal error in their automated processes.

II. LITERATURE REVIEW

XYZ gantry systems, known for their precision and adaptability, are critical components in various automation, robotics, and manufacturing processes. These systems, which operate along three orthogonal axes (X, Y, and Z), are widely used in applications like 3D printing, CNC machining, and automated material handling. The simplicity of their Cartesian coordinate system allows for highly accurate and reliable movement, which is essential in industries requiring precise operations, such as electronics assembly, automotive manufacturing, and packaging. Recent studies highlight the role of advanced control strategies in enhancing the performance of these gantry systems, particularly in complex environments where accuracy and efficiency are paramount

Several studies have contributed to the development and enhancement of gantry systems, particularly in terms of precision, control, and efficiency in industrial automation. [1] focused on optimizing gantry scheduling in multi-gantry production systems, using an online task allocation method to improve throughput and reduce idle times in high-speed environments. [2] introduced back stepping boundary control for gantry crane systems, enhancing stability and robustness against disturbances and load variations. [3] proposed a composite approach for high-speed and high-precision positioning in dual-drive gantry systems, optimizing the positioning accuracy required for complex tasks. [4] applied global iterative sliding mode control to biaxial gantry systems, improving precision and reliability in contouring motion tasks. [5] focused on precision coordinated control of gantry multi-axis systems, addressing coupled dynamics and ensuring prescribed performance for complex industrial operations. [6] explored the modelling and synchronized control of dual-drive gantries, introducing composite adaptive feedforward and RISE feedback mechanisms to optimize performance under changing load conditions. [7] presented a customized gantry pick-and-place system for the forging industry, emphasizing the importance of tailored solutions for specialized tasks. [8] contributed to boundary output feedback control in gantry crane systems, utilizing a back stepping approach to ensure system stability and efficiency. These advancements reflect the ongoing integration of sophisticated control strategies and sensor technologies, enhancing the performance of gantry systems in diverse manufacturing and industrial applications. [9] Gantry scheduling research focuses on using smart techniques like online task allocation and reinforcement learning to streamline operations and boost productivity. By analysing disruptions with mathematical models, it aims to improve efficiency, reduce delays, and enhance overall industrial performance.. [10] Research on PLC control systems for large gantry planers highlights the role of variable-frequency drives in boosting precision and efficiency. Douzhang Ding's study emphasizes energy-saving, reliable automation and engineering techniques that enhance machining processes and overall performance effectively. [11Research on low-cost Cartesian robots focuses on making pick-and-place tasks efficient and affordable. Canales et al. showcase innovative, cost-effective designs that maintain functionality, enabling practical automation in limited-resource environments and expanding access to robotics for diverse applications. [12] Research on H-Gantry automation systems highlights the use of advanced electrical systems to improve manufacturing. H. N. Srinivasa Nayaka et al. focus on automating double-disc front brake production, emphasizing precision, adaptability, and efficiency in industrial processes.. [13] Research on adaptive boundary control for gantry crane systems explores ways to tackle uncertainties and disturbances. L. Ma and X. Lou focus on innovative control strategies to boost stability and efficiency, ensuring reliable operation in dynamic environments. [14] Research on dual-drive gantry systems focuses on advanced control designs to enhance precision and performance. W.-A. Chen et al. emphasize innovative strategies to overcome synchronization challenges, improving efficiency and reliability for industrial and automated applications.

III. DESIGN

The design of an XYZ gantry pick-and-place system controlled by a Programmable Logic Controller (PLC) entails the precise coordination of movements across three axes (X, Y, and Z) to ensure accurate object manipulation. The X and Y axes control the horizontal and vertical movements, respectively, while the Z-axis manages up-and-down motions for optimal object handling. The PLC serves as the central controller, executing ladder logic to operate motors, actuators (such as grippers or suction cups), and sensors, including limit switches and proximity sensors. These components work in unison to guarantee precise positioning and to prevent collisions during operation.

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Fig.2.CAD design model

The system's functionality is initiated by a start button, which prompts the gantry to navigate to the target object. Once positioned, the gripper is lowered to pick up the object, after which the system transports it to a predefined location and releases it. The ladder diagram integrates motor control, axis synchronization, and sensor feedback, ensuring smooth and efficient operation. Safety features, such as emergency stop switches and overload protection mechanisms, are incorporated into the design to mitigate the risk of malfunctions and ensure safe operation. Overall, this automated pick-and-place system is designed for high precision and efficiency, making it well-suited for industrial applications that demand rapid and accurate handling of objects.

IV. METHODOLOGY

The methodology for designing and implementing the XYZ gantry system is structured into several key stages. These include system architecture, kinematic modelling, control algorithm design, trajectory planning, and error correction. Each stage integrates hardware and software components to achieve precise and coordinated motion, ensuring efficiency and accuracy in industrial automation tasks. This comprehensive approach ensures the system can meet the high demands of modern manufacturing processes.

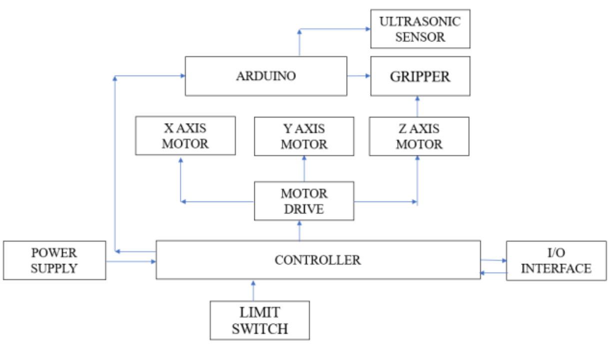

Fig.3.Block Diagram

Fig. 3 shows the system architecture. The XYZ gantry system is made up of a number of interdependent parts. The target coordinates are specified by the user through an easy-to-use interface, which may include command-line instructions or a graphical user interface (GUI).The main component, a Programmable Logic Controller (PLC), processes these inputs and controls every aspect of the system, including communication with the gripper, motor drives, and sensors. Stepper or servo motors that enable rotational and linear motion along the X, Y, and Z axes are controlled by motor drives. The controller receives real-time output from position monitoring sensors like encoders or linear scales, and a pneumatic or servo-driven gripper performs accurate pick-and-place operations. Strong performance is guaranteed under a range of operational circumstances thanks to this tiered integration. In order to compute and reach the intended locations, the system is mathematically using both forward and inverse kinematics. Using the following formulas, forward kinematics determines the gripper's location in

Cartesian coordinates based on joint displacements using the equation

$$X=L_1\cos(\theta_1)+L_2\cos(\theta_1+\theta_2) \quad (1)$$

$$Y=L_1\cos(\theta_1)+L_2\cos(\theta_1+\theta_2) \quad (2)$$

$$Z=d_3 \quad (3)$$

Here, L1 and L2 represent link lengths,theta1 and theta2 are joint angles, and d3 is the linear displacement along the Z-axis. Conversely, inverse kinematics computes the required joint variables to reach a target position X, Y, Z using

$$\theta_2 = cos^{-1}(\frac{X_d^2+Y_d^2-L_1^2-L_2^2}{2L_1L_2}) \quad (4)$$

$$\theta_1 = tan^{-1}\left(\frac{Y_d}{X_d}\right) - tan^{-1}(\frac{L_2\sin(\theta_2)}{L_1+L_2\cos(\theta_2)}) \quad (5)$$

$$d_3 = Z_d$$

This mathematical framework enables accurate calculations for multi-axis coordination, which is critical for precise pick-and-place operations. The control algorithm employs a Proportional-Integral-Derivative (PID) controller to minimize positional errors. The control law is

$$u(t)=K_p e(t) + K\int e(t)dt + K\ \frac{d_e(t)}{dt} \quad (6)$$

where e(t) represents the positional error between the desired and actual positions, and Kp, Ki, Kd are the proportional, integral, and derivative gains, respectively. The algorithm continuously updates feedback and control signals to ensure accurate motion. This real-time feedback loop guarantees high responsiveness and minimizes deviations even under varying load conditions. Trajectory planning is implemented using a trapezoidal velocity profile to ensure smooth and efficient motion. During the acceleration phase, velocity and displacement are defined as:

- Acceleration phase

$$v(t)=a*t, x(t)=\frac{1}{2}at^2 \quad (7)$$

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- Constant velocity phase

$$v(t)=v_{max} \text{ , } x(t)=v_{max} * t \quad (8)$$

- Deceleration phase

$$v(t)=v_{\max - a*t}, \; x(t)=x_{total} - \frac{1}{2} at^2 \quad (9)$$

This ensures a balance between speed and precision. The trajectory planning algorithm is optimized for efficiency, reducing energy consumption while maintaining smooth transitions between acceleration and deceleration phases. Real-time feedback and error correction are achieved using position monitoring sensors. The sensors provide continuous data to the controller, which compares the feedback with the desired positions to calculate positional errors. The controller adjusts the control signals to correct these errors, maintaining high precision and repeatability in operations. Additionally, adaptive control strategies can be employed to handle dynamic changes in system parameters or external disturbances, further enhancing the reliability of the system. The energy consumption of the system is calculated to evaluate its efficiency. The total energy consumed is given by:

$$E = P * t \quad (10)$$

where E is the energy in Joules, P is the power of the motors in Watts, and t is the duration of operation in seconds. Energy efficiency is a critical factor in modern industrial systems, and the XYZ gantry system is designed to minimize power usage without compromising performance. Additional measures, such as regenerative braking and optimized motor configurations, can further enhance energy efficiency.

This methodology outlines the design, control, and operational principles of the XYZ gantry system, emphasizing its precision, efficiency, and scalability for modern industrial automation. By integrating advanced mathematical modelling, robust control algorithms, and energy-efficient designs, the system offers a reliable and cost-effective solution for various industrial applications.

V. GRIPPER MECHANISM

The 2-fingered gear-type gripper utilizes an SG5010 servo motor, which is controlled by a separate Arduino microcontroller and powered by an independent 4V/6V power module. The servo motor drives the gear mechanism, providing precise control over the gripper's finger movement and ensuring accurate opening and closing actions for secure object grasping. The Arduino microcontroller plays a pivotal role in adjusting the gripping force and position according to the specific task requirements, leveraging real-time feedback from sensors or pre-programmed logic. This configuration allows for highly flexible and independent control of the gripper, making it ideal for automated pick-and-place tasks where precision and reliability are crucial. Additionally, the separation of the gripper's control system from the primary robotic or gantry system enhances its adaptability, enabling seamless integration into larger automated workflows without compromising performance.

Fig .4. Gripper

VI. VISUALIZATION AND HMI

In this system, the Human-Machine Interface (HMI) serves as a vital connection between user inputs and the Programmable Logic Controller (PLC), facilitating real-time monitoring and control of the gantry system. The HMI interface provides operators with essential operational data, such as the current floor position, the status of buttons pressed, and the operational condition of the motor, allowing for efficient tracking of the system's performance. This display helps users quickly assess the state of the system and make informed decisions. Additionally, the HMI allows for interaction through the lift box's internal switch panel, enabling operators to input commands such as calling the lift or resetting the system. An emergency stop button is incorporated into the interface, which can immediately halt the system in case of any malfunction or emergency situation, ensuring the safety of both the machine and its surroundings. The system's design ensures that the HMI provides an intuitive and user-friendly interface that enhances the control, safety, and efficiency of the gantry system's operation.

VII. APPLICATIONS

The XYZ gantry system, when integrated with a Programmable Logic Controller (PLC), plays a crucial role in enhancing automation across various industrial sectors. In manufacturing, it is employed for tasks such as material handling, assembly, and CNC machining, where precision and coordination across the three axes (X, Y, and Z) are vital. The PLC acts as the central controller, synchronizing motor and actuator movements based on real-time input from sensors like encoders and proximity detectors. This intelligent control enables tasks such as picking, placing, and manipulating objects with high accuracy, improving productivity, quality control, and reducing material costs. Additionally, the flexibility of real-time adjustments to movement paths and sequences through PLC programming allows the system to adapt to a wide range of tasks and industries.

Furthermore, the integration of proximity sensors and advanced control strategies enhances the gantry system's performance, enabling it to navigate complex environments

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while avoiding obstacles and ensuring safety. In high-speed applications, such as automated warehouses or assembly lines, the PLC-controlled XYZ gantry system maintains efficiency and precision even with varying load conditions. With built-in safety features, such as emergency stops and overload protection, the system can operate autonomously, reducing the need for human intervention. Overall, the application of the XYZ gantry system in automation not only boosts operational efficiency but also contributes to sustainability by optimizing energy use and minimizing waste, making it an essential tool in modern industrial and manufacturing processes.

Table 1: Comparison of existing and proposed methodology

Sl no	Title	Methodology	Controller	Precision	Result
1	Gantry Scheduling for Multi-Gantry Production System by Online Task Allocation Method	Online task allocation for optimizing gantry scheduling in multi-gantry production systems	Online Task Allocation	Not Applicable	Effective scheduling for increased productivity
2	Backstopping Boundary Control for a Class of Gantry Crane Systems	Back stepping control methodology for boundary control of gantry crane systems	Back stepping Boundary Control	Not Specified	Improved control accuracy and stability
3	A Composite High-Speed and High-Precision Positioning Approach for Dual-Drive Gantry Stage	Composite control approach combining high-speed and high-precision positioning for dual-drive gantry.	Composite High-Speed Positioning	±0.01 mm	Enhanced positioning speed and precision
4	Global Iterative Sliding Mode Control of an Industrial Biaxial Gantry System for Contouring Motion Tasks	Iterative sliding mode control for contouring motion in biaxial gantry systems	Sliding Mode Control	±0.02 mm	Improved contouring performance
5	Precision Coordinated Control of Gantry Multi-Axis Systems With Coupled Dynamics and Prescribed Performance	Coordinated control strategy considering coupled dynamics and ensuring prescribed performance	Coordinated Control	±0.005 mm	High-precision coordinated control
6	Modelling and Synchronized Control of a Dual-Drive "Checkerboard" Gantry	Dual-drive gantry control using adaptive feedforward and RISE feedback techniques.	Synchronized Control	±0.01 mm	Effective synchronized control
7	A Customised Gantry Pick and Place System for Forging Industries	Customized design and implementation of gantry systems for pick-and-place operations in forging.	Customised System	±0.1 mm	Custom solution for specific industry needs
8	Boundary Output Feedback Control for A Class of Gantry Crane Systems via Back stepping Approach	Boundary output feedback control using a back stepping approach for gantry crane systems.	Output Feedback Control	Not Specified	Enhanced boundary control
9	Gantry Scheduling for Multi-Gantry Production System by Online Task Allocation Method	Online task allocation for enhancing gantry production efficiency.	Online Task Allocation	Not Applicable	Effective scheduling for increased productivity
10	PLC control system design of large gantry planer based on variable-frequency drives	Design of a PLC-based control system employing variable-frequency drives for large gantry planers.	PLC Control	±0.05 mm	Improved control system design
11	**XYZ Gantry: A PLC-Based Automated Pick-and-Place Robot for Precision Handling**	**The XYZ Gantry involves designing, programming, and deploying a precision PLC system.**	**PLC Control**	**±0.1 mm**	**Improved control system design and user friendly system**

VIII. RESULT

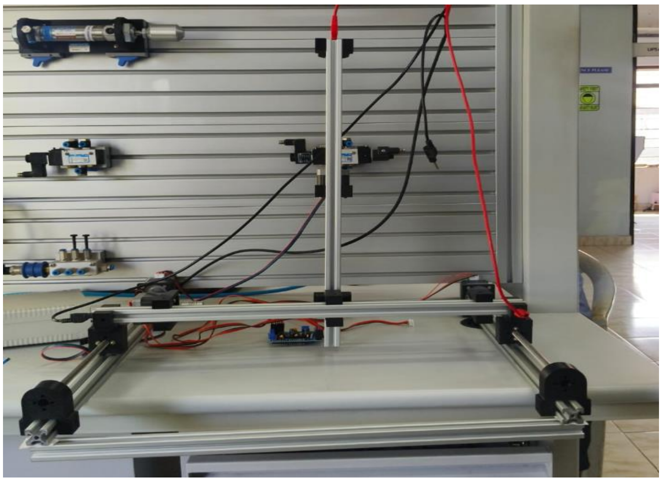

Fig.5.Gantry System

IX. CONCLUSION

The XYZ gantry system is a critical innovation in industrial automation, offering key advantages in precision, efficiency, flexibility, and scalability. Its ability to automate tasks across three axes improves productivity, reduces costs, and enhances product quality in industries such as manufacturing, 3D printing, CNC machining, and material handling. By minimizing human intervention in repetitive tasks, the system ensures consistent output and accuracy, helping manufacturers meet stringent production standards

Additionally, the XYZ gantry system fosters socio-economic growth by creating skilled job opportunities and enabling small and medium-sized enterprises to access advanced automation technology, thereby enhancing global competitiveness. It also contributes to sustainability by reducing material waste and optimizing energy usage. Ultimately, the XYZ gantry system is essential for advancing industrial automation, driving innovation, and supporting eco-friendly manufacturing practices, positioning it as a key factor in shaping the future of global manufacturing.

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