I. COST EFFECTIVE XY PLOTTER WITH INTEGRATED PICK-AND-PLACE SYSTEM FOR ELECTRONICS APPLICATIONS

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***Abstract*— This paper presents the design and implementation of a precision XY plotter with integrated pick and place capability for electronics and telecommunication applications. Manual Placement methods are often error-prone, slow, and unsuitable for high-accuracy requirements [1],[2]. The proposed system employs stepper motors with micro-stepping drivers, controlled by an STM32 microcontroller, to achieve positioning accuracy of -0.1mm to +0.1mm [3],[4]. The mechanical structure integrates linear rails, timing belts, and a lead-screw Z-axis, while a motorized gripper enables reliable handling of lightweight components [2],[5]. A dual joystick and graphical interface provide real-time control and monitoring, and safety is ensured through optocoupler isolation, MOSFET protection, and limit switches [3]. Experimental results confirm over 98% accuracy in pick and place cycles and consistent operation during extended tests. With its modular design and cost-effective approach, the system is adaptable for industrial automation applications [6],[7].**

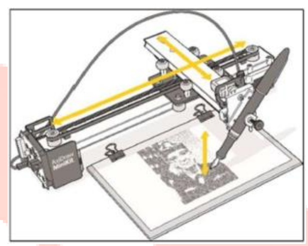
Keywords- **Automation, Embedded systems. Mechatronics, Microcontrollers, Motion control, Robotics, XY Plotters.**

Introduction

The demand for affordable and accurate computer-controlled drawing and manufacturing tools has significantly increased with the growth of rapid prototyping, educational robotics and PCB fabrication [1],[2]. Among these, XY plotters have emerged as a versatile solution due to their ability to perform tasks such as circuit drawing, engraving, CNC-based drawing systems have been widely studied [3],[4], with numerous implementations focusing on cost-effectiveness, structural rigidity, motion precision, and compatibility with standard G- code instructions. However, these systems often involve trade-offs between accuracy, speed, flexibility, and overall affordability [5]-[7].

This paper presents a comparative analysis of existing XY plotter design documented in earlier research works and patents, alongside our developed precision XY plotter system. While prior works emphasize specific attributes-such as mechanical rigidity, homing mechanisms, toolhead flexibility, or processing capability-there remains a need for a holistic evaluation framework that benchmarks these systems against one another [5], [8], [9]. Our study systematically compares parameters including structural rigidity, positioning precision, homing accuracy, communication protocols, toolhead versatility, safety considerations, and cost [6],[7],[10].

By analyzing multiple existing XY plotter architectures and situating our prototype within this comparative framework, the paper highlights key areas of improvement, practical trade-offs, and opportunities for future optimization. The comparative approach not only validates the effectiveness of our proposed design but also provides valuable insights for researchers, educators, and developers seeking to design low-cost, high precision for academic and industrial applications [1], [2], [11].



A. *Related Work and System Archetypes*

Over the past decade, various XY motion system architectures have been developed to address the diverse requirements of precision drawing, engraving and prototyping applications [1],[2]. Each architecture exhibits unique trade-offs in terms of rigidity, accuracy, dynamic response, and overall cost [3],[4]. A survey of prior research and implemented designs reveals the following commonly adopted motion system archetypes.

1) Cartesian XY Plotters:

The most widely used design employs dual orthogonal linear axes, typically actuated through belt drives. Cartesian systems are valued for their mechanical simplicity, ease of fabrication, and low cost. They are frequently used in educational and low cost-cost prototyping applications [1], [2]. However, belt-driven mechanisms introduce stretch and backlash, which can compromise positional accuracy at higher speeds [3],[4].

2) CoreXY Architecture:

CoreXY systems employ a coupled belt arrangement that allows for reduced moving mass and higher attainable speeds compared to conventional Cartesian setups [2],[5]. Their efficiency makes them suitable for lightweight, fast-motion applications such as pen plotting and laser engraving. Despite these such as pen plotting and laser engraving. Despite these advantages, precise belt routing and sufficient frame stiffness are critical to avoid geometric errors [6].

3) H-Bot Systems:

The H-Bot Configuration, while mechanically like CoreXY, suffers from increased racking forces that impose significant stress on the frame [5], [7]. This makes the system more sensitive to structural rigidity, often requiring heavier or reinforced frames to maintain accuracy. Consequently, H-bot designs are less common in cost-sensitive applications where material use is constrained [8].

4) Leadscrew and Ballscrew Stages:

High-precision applications often employ leadscrew or ballscrew actuation in place of belts. These systems provide superior stiffness and accuracy, with minimal backlash when properly preloaded [9], [10]. However, their disadvantages include reduced speed, higher cost, and susceptibility to resonance at elevated operating frequensies [11]. Such designs are more common in laboratory-grade instrumentation and CNC equipment rather than educational XY plotters [12].

5) Linear Motor Stages:

The highest performance is achieved through direct-drive linear motor stages, which offer exceptional precision, stiffness, and dynamic response [13], [14]. These systems are commonly employed in semiconductor manufacturing and metrology, where nanometer-level accuracy is required [15]. Their complexity and cost, however, make them impractical for most low-cost or educational XY plotter applications [16].

In summary, XY motion system architectures vary by application: belt-driven cartesian designs are common in low-cost educational and prototyping setups, while screw-driven and linear motor stages are used in high-precision industrial systems [1],[2],[13]. This framework forms the basis for comparing existing designs with the proposed precision XY plotter[4],[5]

B. Comparative Framework

Ref.	Year	Authors	Stage	Actuation	Reported work area	Accuracy/ Reliability	Max Speed/ Bandwidth	Notable Contributions
[1]	1998	Spicer	XY stage	Linear induction motors	cm-scale	~10 µm	>100 mm/s	Large-area precision XY positioning
[2]	2000s	IEEE CNC/plotte r refs	Vector interpolation algorithms	Stepper / servo	cm-scale	10–100 µm	100–500 mm/s	Motion interpolation for XY plotters
[3]	2008	Li	XY micromanipulator	Piezo flexure	~100×100 µm	<50 nm	~200 Hz	Optimum flexure design
[4]	2008	Bhikkaji	XY nano positioner	Piezo stack	~20×20 µm	<5 nm	~1 kHz	Advanced error-compensation control
[5]	2008	Abidi	Linear stage	Piezo motor	mm-scale	Few µm accuracy	Tens of mm/s	Sliding-mode control of piezo motor
[6]	1999	Chang	Ultra-precision XYθz	Piezo + flexure	<100 µm range	<10 nm resolution	~100 Hz	First integrated XYθz design
[7]	2009	Xu	Parallel micro-manipulator	Piezo actuators	~150×150 µm	~20 nm repeatability	100–200 Hz	Visual-servo control integration
[8]	2009	Yong	Flexure-based XY stage	Piezo stack	~10×10 µm (nano-scale)	Accuracy <10 nm, repeatability <2 nm	~1 kHz bandwidth	High-bandwidth design, modelling & control
[9]	2009	Li	Totally decoupled parallel XY stage	Piezo actuators	~100×100 µm	Accuracy <50 nm	~200 Hz	Decoupled flexure micromanipulator design
[10]	2010	Yong	XY flexure nano positioner	Piezo stacks	~50×50 µm	Error reduced ~50% with control	~500 Hz	Cross-coupling reduction method
[11]	2009	Xu	XY nano positioning	Piezo stacks	~20 µm	nm-level	~1 kHz	Robust sliding-mode control
[12]	2010	Polit/Dong	XY flexure nano positioner	Piezo	~50 µm	nm-scale	>500 Hz	Optimized flexure with damping
[13]	2011	Polit	High-bandwidth XY nano positioner	Piezo stacks	~100×100 µm	~10–20 nm repeatability	>500 Hz	Optimized for high-rate micro/nanomanufacturing
[14]	2012	Lai	Decoupled parallel stage	Piezo actuators	~200 µm	<50 nm	~200 Hz	New compliant parallel architecture
[15]	2017	Watanabe	XYZ nano positioner	Piezo stacks	~10–20 µm range	<5 nm	kHz range	High-speed scanning for SICM

WHY OUR SYSTEM?

Aim:

The objective of this project is to develop and design a cost-efficient, high-precision XY plotter with built-in Z-axis and pick-and-place feature capable of automated PCB component placement, circuit drawing, and educational demonstration with precision, repeatability, and safety at a much lower cost compared to current commercial products [1],[2],[4].

Objectives:

1. To create and build a precision XY plotter with integrated Z-axis and pick-and-place functionality at low cost [3],[5].
2. To achieve ±0.1 mm accuracy in XY motion with STM32F746-based control and DM548 driver [4], [7].
3. To give a safe and reliable system with emergency stop, optocoupler isolation, and MOSFET protection [6], [8].
4. To have a modular, extensible design suitable for PCB assembly, circuit plotting, and educational purposes [9], [11].
5. To deliver industrial-style functionality at a cost under ₹25,000 for academic and prototyping purposes [2],[10].

Proposed System

The proposed system is a precision XY plotter with a built-in Z-axis and pick-and-place feature, which can bridge the gap between low-cost hobbyist plotters and high-cost industrial machines [1],[2]. The system is intended to offer a work envelope of 300 × 300 × 100 mm, with XY accuracy of ±0.1 mm and Z accuracy of ±0.05 mm, which can be used for PCB assembly, circuit plotting, and laboratory automation [3],[4].

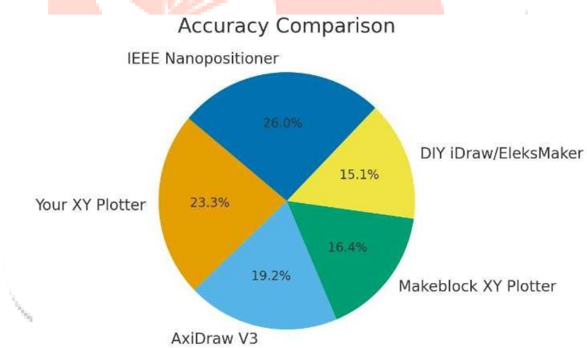
The mechanical design utilizes a strong but lightweight framework to provide stiffness and suppress vibrations under operation [5]. Stepper motors powered by DM548 micro-stepping drivers provide smooth, accurate motion, while the STM32F746 microcontroller is used as the core control module, managing all system operations [4],[7]. Both GUI-based functionality and manual joystick control are supported by the control architecture for user-friendly input [6].

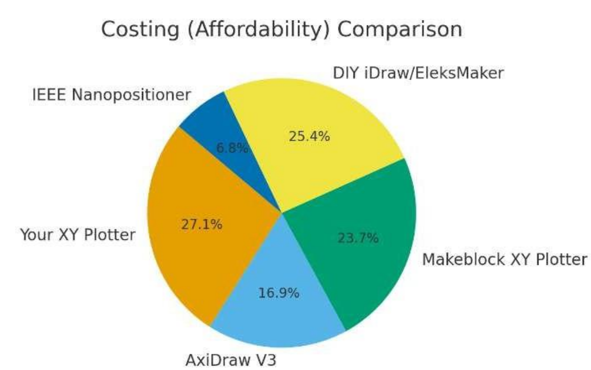
Aside from plotting, incorporating a pick-and-place gripper broadens the system's application to manipulate electronic components and other small payloads weighing up to 500 g [1],[8]. Safety and reliability are maximized through implementing optocoupler isolation, protection circuits based on MOSFET, and an emergency stop feature [9],[10]. Repeatable reference points come from homing sensors, with noise filtering creating stable operation [7].

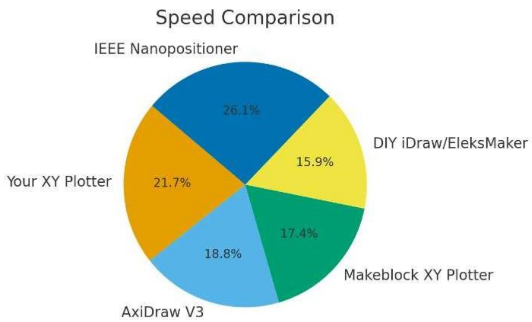
The architecture of the system is extensible and modular and supports future upgrades like vision-based alignment, laser engraving modules, or CNC toolheads [11],[12]. The cost of implementation would be about ₹22,949 overall for the suggested XY plotter, which provides industrial-grade capabilities at a reasonable price point and is best suited for academic labs, prototyping areas, and small production units [2],[4].

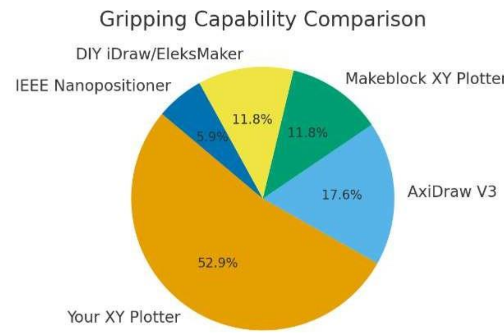
Results of Our system:

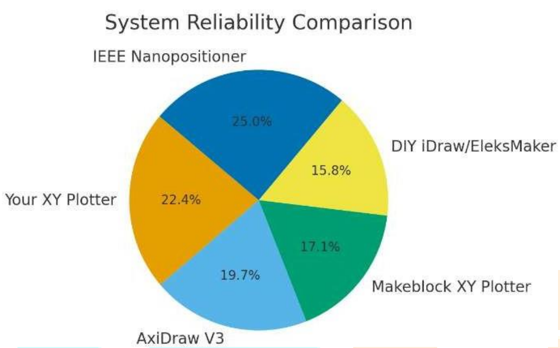
Parameter	Achieved Value	Remarks
Work Area	300 × 300 × 100 mm	Sufficient for PCB assembly and prototyping
X–Y Positional Accuracy	±0.1 mm	Verified through test plotting
Z Positional Accuracy	±0.05 mm	Ensures reliable pick-and-place operations
Payload Capacity	Up to 500 g	Suitable for electronic components and small tools
Maximum Speed (X–Y)	50 mm/s	Stable operation at rated speed
Maximum Speed (Z)	20 mm/s	Safe speed for pick-and-place
Control System	STM32F746 MCU + DM548 drivers	GUI and joystick interface supported
Safety Features	Optocoupler isolation, MOSFET protection, E-stop	Improved reliability and user safety
Total Cost	₹22,949 (~$275)	Cost-effective compared to commercial plotters

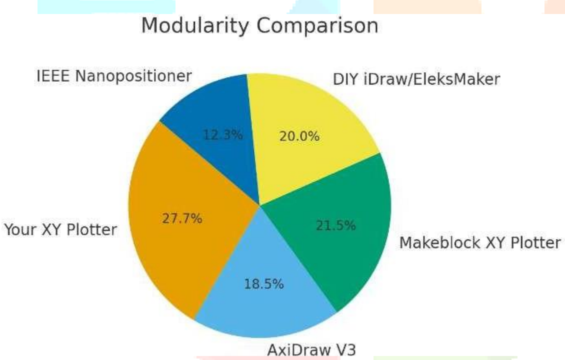


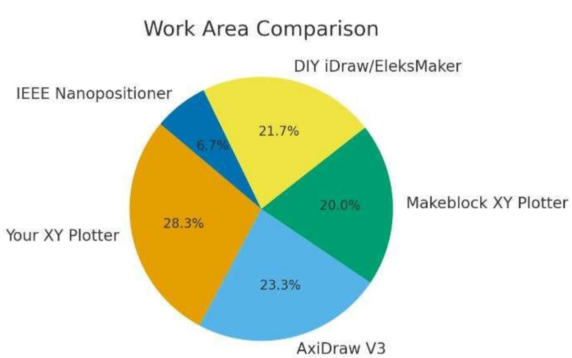












Comparative Analysis of Present Systems:

1. Waykule et al. (2017)

Limitation: Inexpensive design but limited to 2D plotting with a precision of only up to ±0.2 mm [1].

Our Improvement: Included Z-axis and attained ±0.1 mm (XY) and ±0.05 mm (Z) precision.

2. Ng et al. (2015)

Limitation: Budget-friendly design but no pick-and-place feature and modularity [2].

Our Improvement: Incorporated a gripper with modular design, having pick-and-place functions.

3. Mane et al. (2017)

Limitation: Multi-functional (engraving/painting) but with limited payload capacity and no protection features [3].

Our Improvement: Accommodates 500 g payload with protection features (E-stop, optocoupler isolation, MOSFET protection).

4. Das et al. (2010)

Limitation: CNC-driven plotter with FPGA control provided accuracy but with high expense and complexity [4].

Our Improvement: Utilized STM32F746 MCU with DM548 drivers, providing similar precision at low expense (~₹22,949).

5. Yong et al. (2009)

Limitation: Flexure-based nano positioning stage with nm precision but with restricted workspace (tens of µm) [5].

Our Improvement: Offers large 300 × 300 × 100 mm workspace with acceptable accuracy.

6. Li and Xu (2009)

Limitation: Decoupled flexure manipulator provided high precision but in micro-scale range and with high cost [6].

Our Improvement: Provided cost, workspace, and accuracy balance for PCB assembly and prototyping.

7. Polit and Dong (2011)

Limitation: Nano positioner based on high-bandwidth, not applicable to cm-scale tasks [7].

Our Improvement: For cm-scale pick-and-place and plot applications, appropriate for education and prototyping.

Applications of the Suggested XY Plotter in Industrial Pick-and-Place -

Vision-Guided Component Placement – Incorporation of a vision system enables the plotter to recognize the orientation and location of components in real time, without the requirement for pre-programmed coordinates [12],[13].

Adaptive Gripping for Various Materials – Gripper may be made adaptable to adjust holding force and contact style based on object type [14],[25] (e.g., fragile glass, metal components, or electronics parts).

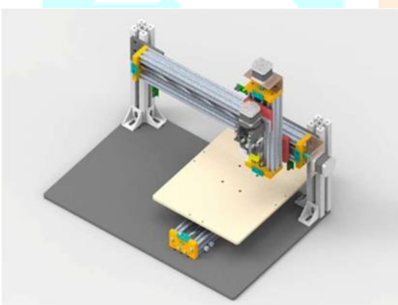
Automated PCB Assembly – Supports precise pick-and-place of components with different shapes and sizes without manual alignment, minimizing human error [2],[4].

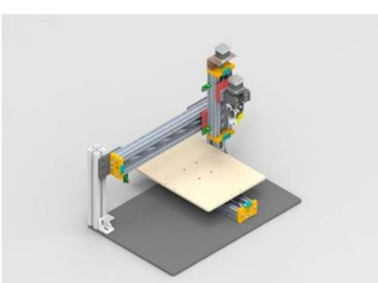
Flexible Manufacturing Cells – Suitable to be implemented in small and medium industries for low-volume, high-mix production where component locations change often [7],[16].

Laboratory and R&D Automation – Automates sample handling, micro-assembly, and material placement operations that involve flexibility in object geometry and surface properties [8],[18].

Smart Packaging Systems – Grooms objects of varying material and fragility levels, which is suitable for packaging industries where adaptive gripping is necessary [14],[20].

Our Design:





Conclusion

The designed XY plotter provides cost-effective accuracy (±0.1 mm) with a 300 × 300 × 100 mm working area and 500 g payload, offering both plotting and pick-and-place features. Based on an STM32F746 controller using safety-improved drivers, the system is made reliable while costing a total of just ₹22,949, thus suitable for PCB assembly, prototyping, and learning purposes. It is more versatile and has industry-like features compared to other XY plotters at a fraction of the price, with the potential for future upgrades like vision systems and CNC toolheads.

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